Daylighting Systems 4.

Introduction 4.1.

This chapter describes the characteristics of advanced daylighting systems, to aid building professionals in choosing a system. Following this introduction, which summarises the key elements of the decision-making process for daylighting systems, Section 4.2 consists of a detailed matrix of daylighting systems classified into two general groups: those with and without shading. The technical descriptions in Sections 4.3 through 4.14 give details about the design and application of each system, the physical principles on which it is based, as well as information about controls, maintenance, costs and energy savings, examples of use, and simulation or measurement results of the performance associated with each system.

The systems in this chapter represent the large range of advanced daylighting systems now available to the building profession. Some of these systems are still in the development or prototype stage and some systems are architectural concepts rather than products (see Chapter 2).

All of these systems have different characteristics related to the major performance parameters discussed in Chapter 3. Because these parameters may have different importance in real-life design cases, it is impossible to develop a unified rating scale or to define a clear-cut selection method for choosing the best daylighting system in a given situation. Nonetheless, there are some general strategies for making decisions about using a daylighting system in a design.

First, a designer should focus on these questions; Chapter 2 discusses in detail the conditions that will govern the answers:

- Is it useful to apply a daylighting system in my case?
- What kind of problems can I resolve with a daylighting system?

- What benefits could I achieve with a daylighting system?

If the use of a daylighting system appears to be a promising option based on this initial screening, the next question is:

- Which system should I choose?

This chapter presents the most comprehensive and up-to-date information available, including measured performance data and expert analysis, to assist designers in answering that question.

The key parameters to consider in choosing a system are:

- Site daylighting conditions—latitude, cloudiness, obstructions
- Daylighting objectives
- Daylighting strategies implied in the architectural design
- Window scheme and function
- Energy and peak power reduction objectives
- Operational constraints—fixed/operable, maintenance considerations
- Integration constraints—architectural/construction integration
- Economic constraints

It is also important to focus on the major objectives for applying daylighting systems:

- redirecting daylight to under-lit zones
- improving daylighting for task illumination
- improving visual comfort, glare control
- achieving solar shading, thermal control.

It is very important that a reader who wishes to compare the merits of different systems understand the context of the results given in this chapter. Some measurement results come from scale-model experiments under simulated light conditions while others come from full-scale test rooms under real sky conditions at different locations around the world (see testing facility descriptions given in Appendix 8.4). Because experimental test rooms and conditions differ so significantly from site to site, we cannot compare the numerical results from different experimental sites. The general conclusions drawn for each system are valid, but specific details, such as the absolute magnitude of illumination levels, cannot be compared among systems tested at different sites.

4.2. System Matrix

The matrix that follows covers two groups of daylighting systems—those with and without shading.

Daylighting Systems with Shading

Two types of daylighting systems with shading are covered: systems that rely primarily on diffuse skylight and reject direct sunlight, and systems that use primarily direct sunlight, sending it onto the ceiling or to locations above eye height.

Shading systems are designed for solar shading as well as daylighting; they may address other daylighting issues as well, such as protection from glare and redirection of direct or diffuse daylight. The use of conventional solar shading systems, such as pull-down shades, often significantly reduces the admission of daylight to a room. To increase daylight while providing shading, advanced systems have been developed that both protect the area near the window from direct sunlight and send direct and/or diffuse daylight into the interior of the room.

Daylighting Systems Without Shading

Daylighting systems without shading are designed primarily to redirect daylight to areas away from a window or skylight opening. They may or may not block direct sunlight. These systems can be broken down into four categories:

> **Diffuse Light-Guiding Systems** redirect daylight from specific areas of the sky vault to the interior of the room. Under overcast sky conditions, the area around the sky zenith is much brighter than the area close to the horizon. For sites with tall external obstructions (typical in dense urban environments), the upper portion of the sky may be the only source of daylight. Light-guiding systems can improve daylight utilisation in these situations.
>
> **Direct Light-Guiding Systems** send direct sunlight to the interior of the room without the secondary effects of glare and overheating.
>
> **Light-Scattering or Diffusing Systems** are used in skylit or toplit apertures to produce even daylight distribution. If these systems are used in vertical window apertures, serious glare will result.
>
> **Light Transport Systems** collect and transport sunlight over long distances to the core of a building via fiber-optics or light pipes.

Some Notes on the Information in the Matrix

Some systems included in the matrix can fulfil multiple functions and are therefore shown in more than one category. Light shelves, for instance, redirect both diffuse skylight and beam sunlight.

Selected column headings from the matrix that are not self-explanatory are described in detail below:

Under the heading “Glare protection,” the following questions were considered: Does the system prevent glare when viewed directly from the interior, glare from direct sun, and glare from veiling reflections?

In evaluating “View outside,” the matrix considers the following questions: Does the system permit a transparent, undistorted view when used in its primary design position? For example, the systems known as anidolic zenithal openings do not permit a clear unobstructed view to the exterior (they are typically used above a transparent window which does permit an unobstructed view).

For the column headed “Light-guiding into the depth of the room,” the matrix answers the question: Does the system achieve light redirection to depths that are greater than conventional perimeter window systems?

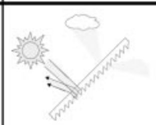
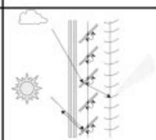
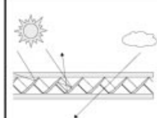
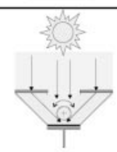
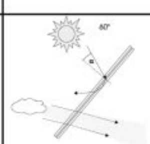
In the column “Homogeneous illumination,” the matrix addresses the question: Does the system achieve a uniform distribution of daylight throughout a space (walls and ceiling)? In assessing “Savings potential (artificial lighting),” the matrix answers the question: Does the system effectively displace the use of artificial lighting compared to conventional systems?

In the column headed “Need for tracking,” the matrix answers the question: Are passive adjustments or mechanical systems needed to track the diurnal or seasonal movement of the sun throughout the day or year to maintain efficient performance?

“Availability” indicates whether the technology is commercially available (A) or is still in the testing stage (T). Contact information for manufacturers of commercially available systems is given in Appendix 8.6. Some systems that are labeled as available must be designed and constructed as an integral part of the building envelope, e.g., light shelves.

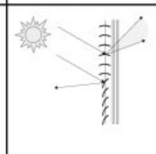
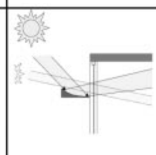
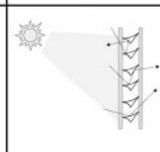
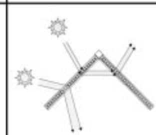
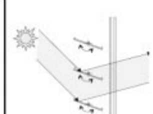
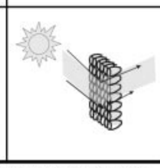
For most of the systems included, detailed information is given in the technical descriptions that follow the matrix. An important exception is light transport systems (group 2D), which were beyond the scope of this work.

1. Shading Systems

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving potential (artificial lighting)	Need for tracking	Availability
1A Primary using diffuse skylight	Prismatic panels (→ 4.5)		All climates	Vertical windows, skylights	D	N	D	D	D	D	A
	Prisms and venetian blinds		Temperate climates	Vertical windows	Y	D	Y	Y	Y	Y	A
	Sun protecting mirror elements		Temperate climates	Skylights, glazed roofs	D	N	N	Y	N	N	A
	Anidolic zenithal opening (→ 4.12, 4.13)		Temperate climates	Skylights	Y	N	N	Y	Y	N	T
	Directional selective shading system with concentrat-ing Holo-graphic Optical Element (HOE) (→ 4.11)		All climates	Vertical windows, skylights, glazed roofs	D	Y	N	D	Y	Y	T
	Transparent shading system with HOE based on total reflection (→ 4.11)		Temperate climates	Vertical windows, skylights, glazed roofs	D	Y	N	Y	Y	Y	A

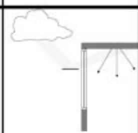
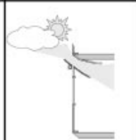
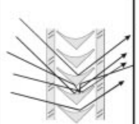
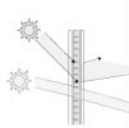
Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

1. Shading Systems

Category	Type/name		Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
1B Primary using direct sunlight	Light guiding shade (→ 4.7)		Hot climates, sunny skies	Vertical windows above eye height	**Y**	**Y**	**D**	**D**	**D**	**N**	**T**
	Louvres and blinds (→ 4.4)		All climates	Vertical windows	**Y**	**D**	**Y**	**Y**	**Y**	**Y**	**A**
	Light shelf for redirection of sunlight (→ 4.3)		All climates	Vertical windows	**D**	**Y**	**Y**	**Y**	**Y**	**N**	**A**
	Glazing with reflecting profiles (Okasolar)		Temperate climates	Vertical windows, skylights	**D**	**D**	**D**	**D**	**D**	**N**	**A**
	Skylight with Laser Cut Panels (LCPs) (→ 4.7)		Hot climates, sunny skies, low latitudes	Skylights	**D**		**Y**	**Y**	**Y**	**N**	**T**
	Turnable lamellas		Temperate climates	Vertical windows, skylights	**Y/D**	**D**	**D**	**D**	**D**	**Y**	**A**
	Anidolic solar blinds (→ 4.13)		All climates	Vertical Windows	**Y**	**D**	**Y**	**Y**	**D**	**N**	**T**

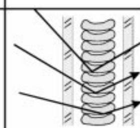
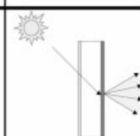
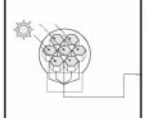
Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

2. Daylighting systems without shading included

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
2A Diffuse light guiding systems	Light shelf (→ 4.3)		Temperate climates, cloudy skies	Vertical windows	**D**	**Y**	**D**	**D**	**D**	**N**	**A**
	Anidolic Integrated System (→ 4.12)		Temperate climates	Vertical windows	**N**	**Y**	**Y**	**Y**	**Y**	**N**	**A**
	Anidolic ceiling (→ 4.12)		Temperate climates, cloudy skies	Vertical facade above view-ing window		**Y**	**Y**	**Y**	**Y**	**N**	**T**
	Fish System		Temperate climates	Vertical windows	**Y**	**D**	**Y**	**Y**	**Y**	**N**	**A**
	Zenith light guiding elements with HOEs (→ 4.10)		Temperate climates, cloudy skies	Vertical windows (especially in court-yards), skylights		**Y**	**Y**	**Y**	**Y**	**N**	**A**
2B Direct light guiding Systems	Laser Cut Panel (→ 4.6)		All climates	Vertical windows, skylights	**N**	**Y**	**Y**	**Y**	**Y**	**N**	**T**
	Prismatic panels (→ 4.5)		All climates	Vertical windows, skylights	**D**	**D**	**D**	**D**	**D**	**Y/N**	**A**

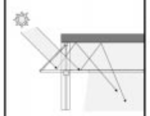
Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

2. Daylighting systems without shading included

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements: Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
2B Direct light guiding Systems	HOEs in the skylight		All climates	Skylights	D	Y	Y	Y	Y	N	A
	Sun-directing glass (→ 4.9)		All climates	Vertical windows, skylights	D	N	Y	Y	Y	N	A
2C Scattering systems			All climates	Vertical Windows, skylights	N	N	Y	Y	D	N	A
2D Light transport	Heliostat		All climates, sunny skies				Y		Y	Y	A
	Light Pipe		All climates, sunny skies				Y	Y	Y	N	A
	Solar Tube		All climates, sunny skies	Roof			Y	D	Y	N	A
	Fibres		All climates, sunny skies				Y		Y	Y	A

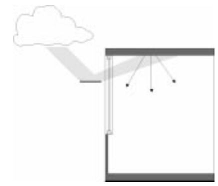
Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

2. Daylighting systems without shading included

Category	Type/name	Sketch	Climate	Location	Criteria for the choice of elements						
					Glare protection	View outside	Light guiding into depth of room	Homogeneous illumination	Saving of energy for artificial lighting	Need for tracking	Availability
2D Light transport	Light-guiding ceiling		Temperate climates, sunny skies				**Y**	**Y**	**Y**	**N**	**T**

Y= Yes , D= Depends, N= No, A= Available, T= Testing phase, "→ n" = See section number n

4.3. Light Shelves



A light shelf is a classic daylighting system, known to the Egyptian Pharaohs, that is designed to shade and reflect light on its top surface and to shield direct glare from the sky.

4.3.1. Technical Description

Components

A light shelf is generally a horizontal or nearly horizontal baffle positioned inside and/or outside of the window facade. The light shelf can be an integral part of the facade or mounted on the building.

Figure 4-3.1: Semi-transparent double light shelves made out of reflective glass [Littlefair 1996]

Production

Light shelves are not standard, off-the-shelf products. They must be made to fit the architectural situation in which they are used.

Location in Window System

A light shelf is usually positioned above eye level. It divides a window into a view area below and a clerestory area above. Light shelves sometimes employ advanced optical systems to redirect light to deep areas of the building interior. The light shelf is typically positioned to avoid glare and maintain view outside; its location will be dictated by the room configuration, ceiling height, and eye level of a person standing in the space. Generally, the lower the light shelf height, the greater the glare and the amount of light reflected to the ceiling.

Technical Barriers

An internal light shelf, which redirects and reflects light, will reduce the amount of light received in the interior relative to a conventional window. Both full-scale and scale model measurements have shown that windows with internal light shelves produce an overall reduced daylight factor on the work plane throughout the interior space compared to a non-shaded window of equal size [Aizlewood 1993, Christoffersen 1995, Littlefair 1996, Michel 1998]. In some cases, use of an external light shelf makes it possible to increase the total amount of daylight compared to that provided by traditional windows. An external light shelf increases exposure to the high luminance area near the sky zenith. Depending on the light shelf's geometry, available daylight will be more uniformly distributed by an external light shelf compared to a non-shaded window of equal size.

4.3.2. Application

Light shelves affect the architectural and structural design of a building and must be considered at the beginning of the design phase because they require a relatively high ceiling in order to function effectively. Light shelves should be designed specifically for each window orientation, room configuration, and latitude. They can be applied in climates with significant direct sunlight and are applicable in deep spaces on a south orientation in the northern hemisphere (north orientation in the southern hemisphere). Light shelves do not perform as well on east and west orientations and in climates dominated by overcast sky conditions.

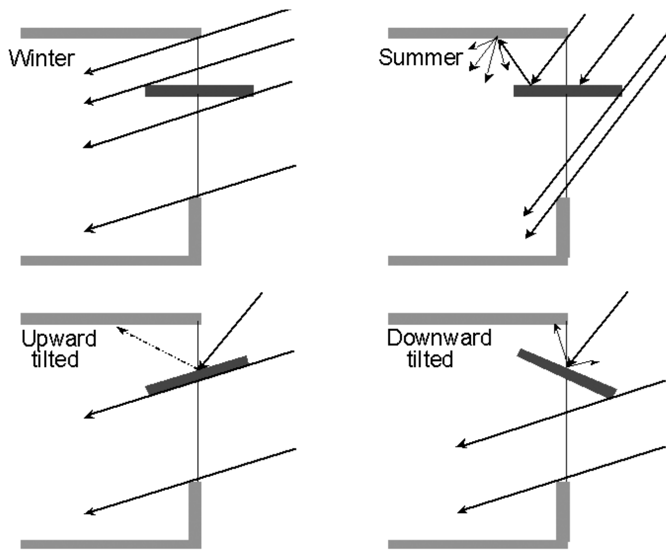


FIGURE 4-3.2: Top section of an interior and exterior light shelf with specular surface, showing the path of sunlight rays in the winter and in the summer. Bottom section shows how an upward- or downward-tilted reflective light shelf influences shading and daylight reflection. Note that, in winter, the light shelf alone does not adequately control glare

4.3.3. Physical Principles and Characteristics

The orientation, position in the facade (internal, external, or combined), and depth of a light shelf will always be a compromise between daylight and shading requirements. An internal light shelf, which redirects and reflects light, will reduce the amount of light received in the interior. For south-facing rooms (in the northern hemisphere), it is recommended that the depth of an internal light shelf be roughly equal to the height of the clerestory window head above the shelf. Moving the light shelf to the exterior creates a parallel movement of shaded area towards the window facade, which reduces daylight levels near the window and improves daylight uniformity. The recommended depth of an external light shelf is roughly equal to its own height above the work plane [Littlefair 1995]. Glazing height and light shelf depth should be selected based on the specifics of latitude and climate.

At low latitudes, the depth of internal light shelves can be extended to block direct sunlight coming through the clerestory window at all times (see Figure 4-3.2). At higher latitudes and with east- or west-facing rooms, a light shelf may let some direct sunlight (low solar elevation) penetrate the interior, through the space between the light shelf and the ceiling, resulting in the need for additional shading devices. Increasing the depth of the shelf will reduce the problem but will also obstruct desired daylight penetration and outside view. Shading the window perimeter by tilting the shelf downward will reduce the amount of light reflected to the ceiling. Upward tilting will improve penetration of reflected daylight and reduce shading effects. A horizontal light shelf usually provides the best compromise between shading requirements and daylight distribution.

The ceiling is an important secondary part of the light shelf system because light is reflected by the light shelf towards the ceiling and then reflected from the ceiling into the room. The characteristics of the ceiling that affect this process are surface finish, smoothness, and slope. Although a ceiling with a specular surface will reflect more light into the room, care should be taken to avoid glare from the ceiling reflections near the light shelf. To avoid glare, the ceiling finish is usually white diffusing or low-gloss paint.

The penetration of light from a light shelf system depends on the ceiling slope. A gable style ceiling that slopes upwards from the window towards the centre of the building will dramatically increase the depth to which light from the light shelf penetrates into the building. For a flat ceiling, light from the light shelf is mostly reflected into the space near the window, so penetration of light into the room is more modest.

Conventional Light Shelf

A light shelf is usually a fixed, solid system, but some fixed external light shelves can incorporate slatted baffle systems with reduced upward reflection. The finish of a light shelf influences the “efficiency” and direction of light redirected from its top to the ceiling. A matte finish produces diffuse reflection with no directional control, in contrast to a specular reflection where the angle of incidence is (almost) equal to the angle of reflection. For a perfectly diffusive surface (Lambertian), only half of the reflected light will be distributed into the room, but, for an interior light shelf, some of the “lost” light is reflected towards the interior from the clerestory glass surface. A highly reflective surface (e.g., a mirror, aluminium, or a polished material) reflects more light to the ceiling than a diffuse surface but may reflect onto the ceiling an image of any dirt pattern on it [Lam 1986]. A semi-specular finish for the top of the light shelf may be better. Another possibility is a reflecting prismatic film to throw light further into the room [Littlefair 1996].

Optically Treated Light Shelf

Optically treated light shelves make two significant improvements over conventional light shelf designs for sunny climates, see Figure 4-3.3: 1) The light shelf geometry is curved and segmented to passively reflect sunlight for specific solar altitudes, and 2) commercially available, highly reflective, semi-specular optical films can increase efficiency [Beltrán et al. 1997]. Design objectives are to block direct sun at all times, to increase daylight illuminance levels up to 10 m from the window wall, to minimise solar heat gains through an optimally sized window aperture, and to improve daylight uniformity and luminance gradient throughout the room under variable direct sun conditions. For consistent performance throughout the year, the optically treated light shelf will project from the exterior wall by 0.1–0.3 m to intercept high summer sun angles. No active adjustment or control is required.

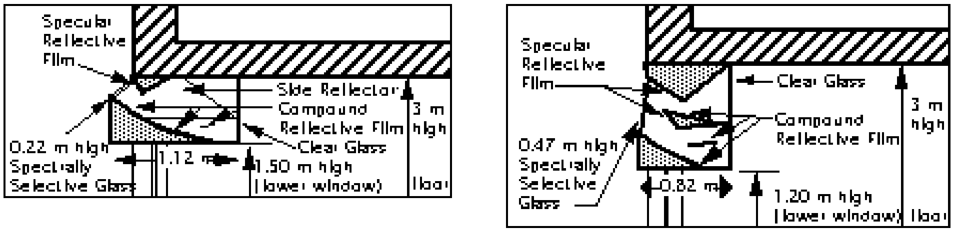


Figure 4-3.3:
Section of light shelf: (left) single-level light shelf, (right) bi-level light shelf

The optically treated light shelf design consists of a main lower reflector and a secondary upper reflector. The lower segmented reflector consists of inclined surfaces that are finished with a daylight film. The film has linear grooves that reflect sunlight within a 12–15° outgoing angle at normal incidence to the grooves. The segments are inclined to reflect sun to the ceiling plane up to 10 m from the window wall for noon solstice and equinox sun angles (south-facing facades in the northern hemisphere). The upper reflector is placed above the main reflector at the ceiling plane near the window to intercept incoming low winter sun angles and to reflect these rays to the lower main reflector. This reflector is surfaced with a highly reflective specular film and may be a small-area source of glare.

This system has been developed conceptually using scale models. A full-scale modified skylight prototype has been built and installed in a small office building [Lee et al. 1996]. For vertical window applications, efficient performance of the system requires a room height greater than 2.5 m from floor to ceiling. It is possible to design and adapt an optically treated light shelf to existing buildings, but special care should be taken to integrate it with existing architectural features.

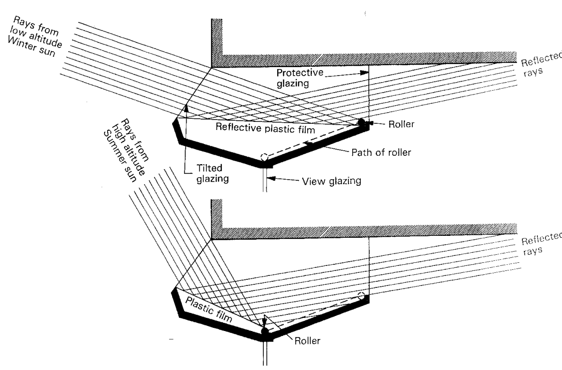


Figure 4-3.4:
Winter and summer operation of the VALRA (Variable Area Light Reflecting Assembly) [Littlefair 1996, Howard et al. 1986]

Sun-Tracking Light Shelf

A variable area light reflecting assembly (VALRA) is a tracking light shelf system (see Figure 4-3.4) that reflects light into a building [Howard et al. 1986]. The system uses a reflective plastic film surface over a tracking roller assembly within a fixed light shelf. This system extends the projection capabilities of a fixed light shelf so that it functions for all sun angles. It has not been installed in a building to date. A simpler version of a light shelf that can be adjusted according to sun position or the sky luminance is the movable (pivotable), external light shelf (see monitored results from Denmark below).

4.3.4. Control

In general, movable light shelves are more expensive (especially if motorized) than fixed light shelves, but movable systems are more flexible in control and application. Downward tilted light shelves shade window perimeters and reduce the amount of light reflected to the ceiling. Upward-tilted light shelves improve penetration of reflected daylight but reduce the shading effect of the window perimeter. Exterior-mounted light shelves reduce cooling loads by providing more shading of direct sun to lower view apertures relative to what is possible with unobstructed windows with or without interior shades. With interior-mounted light shelves, there will be an increase in transmitted direct solar radiation through the non-shaded clerestory window above the light shelf, compared to the light transmitted by a window that has an interior shading device that covers the full height of the window. The type of glazing in the clerestory window and lower view window aperture will also affect solar heat gains.

4.3.5. Maintenance

Light shelves require regular cleaning. An internal shelf collects dust, and an external shelf can become dirty, collect snow, and provide nesting places for birds or insects. A specular surface requires maintenance to maintain its reflective properties. Optically treated light shelves are completely sealed from the interior and exterior environment and protected from dirt and occupant interference. They require no routine maintenance other than cleaning of the exterior and interior glass.

4.3.6. Cost and Energy Savings

Reduced light at a window wall can lead to increased use of electric lighting, but increasing the uniformity of light distribution in the same situation may cause the room to be perceived as relatively well lit, which may reduce the probability that occupants will switch on electric lights. The total amount of daylight can be enhanced by using an external light shelf, depending on the shelf's geometry and surface treatment. However, most traditional light shelves do not, in general, produce high levels of illuminance deep inside a space, so energy savings are modest.

The optically treated light shelf can introduce adequate ambient illuminance for office tasks in a 5 m to 10 m zone of a deep perimeter space under most sunny conditions with a relatively small inlet area. It has been found that a room with the optically treated light shelf can use less total annual electricity for lighting than one with a conventional light shelf.

4.3.7. Some Examples of Use

- De Montfort University Engineering, Leicester, UK: internal light shelf
- Greenpeace, London, UK: external light shelf
- South Staffordshire Water, Walsall, UK: internal and external (sloped) light shelf

- Sacramento Municipal Utility District (SMUD) Headquarters, Sacramento, California, USA: internal sloped Mylar sail light shelf (Figure 4-3.5)
- Lockheed Building 157, Sunnyvale, California, USA: south exterior light shelf with curved segmented shape and north interior flat light shelf (3.7 m deep)
- Palm Springs Chamber of Commerce, Palm Springs, California, USA: Skylight with optically treated light shelf (Figure 4-3.6)

Figure 4-3.5: View of interior/exterior light shelf at the SMUD Headquarters, California

Figure 4-3.6: South side of an optically treated skylight system, Palm Springs, California

4.3.8. Simulations and Measured Results

Measurements were made of three different conventional light shelves with various surface treatments and locations in the facade (interior and exterior).

A.	Exterior light shelf mounted on a pivot with semi-reflective surface	**Denmark**
B.	Interior fixed light shelf with semi-reflective surface	**Norway**
C.	Interior fixed light shelf with semi-transparent surface	**Norway**

Figure 4-3.7: The exterior semi-reflective light shelf in a downward-tilted position

A. Exterior Light Shelf with Semi-Reflective Surface (Denmark)

The Danish Building Research Institute, Denmark (DEN), tested an exterior light shelf (0.8 m deep), shaped like a "flight wing", and mounted on a pivot on the south facade. The surface of the shelf is polished aluminium with 75% reflectance.

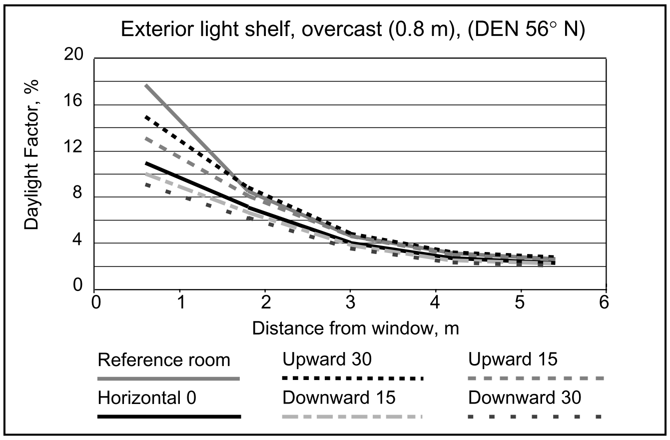
Two identical rooms at the institute were oriented 7° east of due south with some outside obstructions to the west. Each room has windows that extend the full height of the facade, but the lower part of the windows, from the floor to a sill height of 0.78 m, was covered during the measurements (see test room descriptions in Appendix 8.4). The reference room had clear, unshaded glazing.

Light Shelf - Exterior (0.8 m deep) **Denmark: 56°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal - Overcast (DF%)	7.1%	8.6%	4.1%	4.7%	2.3%	2.7%	16.2	6.5
Upward tilted 15° - Overcast (DF%)	8.1%	8.4%	4.6%	4.6%	2.6%	2.6%	12.1	4.8
Upward tilted 30° - Overcast (DF%)	8.8%	8.4%	4.9%	4.6%	2.8%	2.6%	12.9	5.0
Downward tilted 15° - Overcast (DF%)	6.7%	8.5%	3.9%	4.7%	2.2%	2.7%	9.6	3.8
Downward tilted 30° - Overcast (DF%)	6.2%	8.6%	3.5%	4.8%	2.0%	2.7%	11.6	4.7
Horizontal - Clear winter: Noon	Sun	Sun	> 4,000	> 4,000	> 4,000	> 4,000	17.1	52.8
Horizontal - Clear winter: 15:00	880	1040	600	690	380	430	4.3	5.9
Horizontal - Clear equinox: Noon	Sun	Sun	> 4,000	> 4,000	> 4,000	> 4,000	38.6	95.1
Horizontal - Clear equinox: 15:00	6,510	7,250	> 4,000	> 4,000	3,060	3,450	27.5	58.4
Upward tilted 30° - Clear equinox: Noon	Sun	Sun	> 4,000	> 4,000	> 4,000	> 4,000	53.8	96.2
Upward tilted 30° - Clear equinox: 15:00	Sun	Sun	> 4,000	> 4,000	3,830	3,620	33.0	62.1
Horizontal - Clear summer: 9:00	4,030	4,370	2,500	2,760	1,540	1,760	69.5	40.7
Horizontal - Clear summer: Noon	6,700	6,630	3,770	> 4,000	2,270	2,730	96.8	66.5
Upward tilted 30° - Clear summer: Noon	6,400	5,580	> 4,000	> 4,000	3,240	2,670	102.3	70.8
Upward tilted 30° - Clear summer: 15:00	4,710	3,940	3,270	2,700	2,120	1,770	92.9	47.5
Downward tilted 30° - Clear summer: 9:00	2,570	3,350	1,650	2,220	1,040	1,440	71.6	39.3
Downward tilted 30° - Clear summer: Noon	3,190	4,990	2,160	3,610	1,380	2,300	101.5	67.8

Note: The window, intermediate, and rear zone sensors were 1.8, 3.0, and 5.4 m from the window, respectively. "Sun" indicates sunlight striking the sensors. ">4000" indicates that the sensors are at a state of saturation. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing 7° east of due south. DF% is the daylight factor.

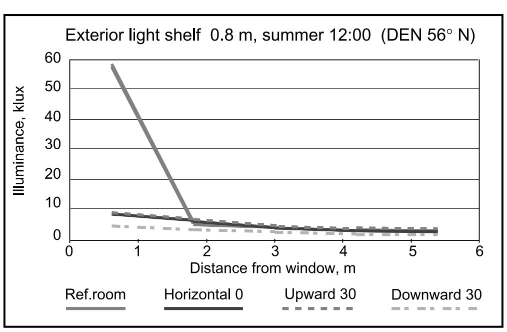
Overcast Sky

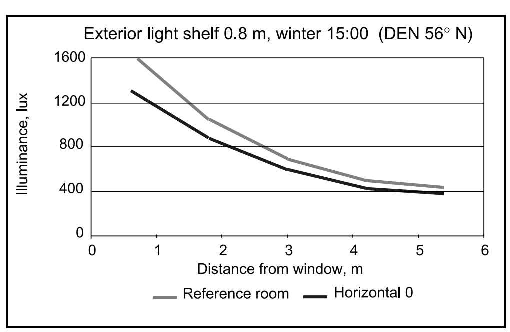
The exterior light shelf shades the window zone and evens out the luminance difference within the room. Five different slope angles were measured. Tilting the light shelf upward (-30°) increases the illuminance level in the intermediate zone compared to illuminance in the reference room which has an unshaded window of equal size. Thus there is, in general, some evening out of luminance variations between the window perimeter and the interior depth of the room.



Clear Sky

In summer, the exterior light shelf completely shades an area near the window from direct sunlight. Reflected sunlight illuminates the ceiling, but only the upward-tilted light shelf (-30°) boosts the illuminance level (10–20% in relative values) at the back of the room. The horizontal light shelf reduces the light level by 10% to 20% in most of the room, and the downward-tilted light shelf (30°) reduces the light level by 30% to 40%. At equinox, the exterior light shelf behaves much as in the summer. The semi-specular surface of the horizontal light shelf reflects sunlight further into the room and increases the illuminance level slightly at the back of the room. The upward-tilted light shelf (-30°) does not increase the illuminance level at the back as it does in summer. The illuminance level is the same as in the reference room because the light shelf does not block direct sunlight coming through the clerestory window. At low sun angles in winter, direct sunlight penetrates the interior through the space below and above the light shelf, resulting in a need for additional shading devices.





Conclusion (A)

A conventional light shelf has limited application in high-latitude countries because additional shading devices will be necessary during much of the year. If used in climates dominated with overcast sky conditions, the light shelf should be tilted. In sunny climates or low-latitude countries, the light shelf will protect areas near the window from direct sunlight with only a slight reduction in light levels throughout the rest of the room. To reduce cooling loads and solar gain, an exterior light shelf is the best compromise between shading requirements and daylight distribution.

B. Interior Light Shelf with Semi-Reflective Surface (Norway)

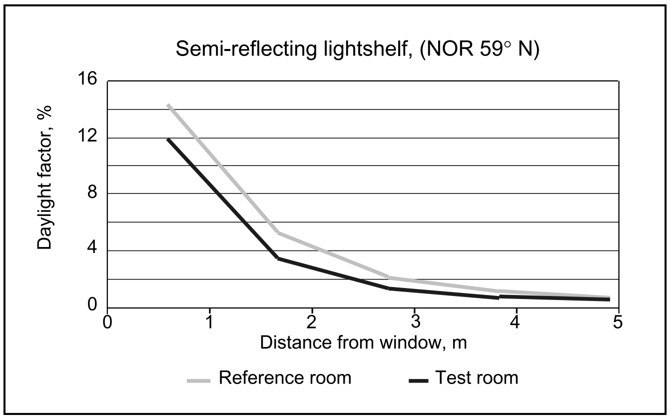
The Norwegian University of Science and Technology, Norway (NOR), tested an interior horizontal light shelf 1.0 m deep, the full width of the window, and mounted between the clerestory window (1.0 m^2) and the view window (2.2 m^2). The surface of the light shelf is covered with a semi-reflective, brushed aluminium sheet. The reference room had clear, unshaded glazing of equal size to the test room. Measurements were made in an occupied office building at Sandvika, Norway (near Oslo) at latitude 59ºN. See detailed test room description in Appendix 8.4.

Interior translucent blinds **UK: 52°N** Monitoring case and time	Interior Illuminance level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	3.6 %	9.0 %	1.7 %	2.9 %	0.5 %	0.7 %	19.6	7.8
Downward 45° - Overcast (DF%)	4.2 %	10.4 %	2.1 %	3.2 %	1.0 %	1.3 %	3.6	1.5
Closed 90° - Overcast (DF%)	2.0 %	8.9 %	0.8 %	2.7 %	0.3 %	0.7 %	8.5	3.4
Horizontal 0° - Clear winter: Noon	3,120	3,920	Sun	Sun	1,110	1,500	29.4	71.3
Horizontal 0° - Clear winter: 15:00	2,100	2,910	1,350	1,690	570	730	12.8	35.8
Horizontal 0° - Clear equinox: Noon	2,790	4,070	1,380	1,500	640	750	55.5	86.5
Horizontal 0° - Clear equinox: 15:00	2,310	3,530	1,150	1,760	520	790	35.1	66.5
Downward 45° - Clear equinox: Noon	1,810	2,390	930	1,130	460	570	77.1	77.4
Downward 45° - Clear equinox: 15:00	1,410	2,550	720	1,220	360	580	56.8	63.2
Closed 90° - Clear equinox: Noon	250	4,450	250	1,700	40	780	NA	NA
Closed 90° - Clear equinox: 15:00	200	3,300	90	1,440	20	640	NA	NA

Note: For overcast sky measurements, the window, intermediate, and rear zone sensors were 1.05, 2.89, and 6.34 m from the window, respectively. For clear sky measurements, the window, intermediate, and rear zone sensors were 2.7, 4.5, and 8.1 m from the window, respectively. The tilt angle is defined as the vertical angle from horizontal where a positive angle is downwards, with a view of the ground from inside the building. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

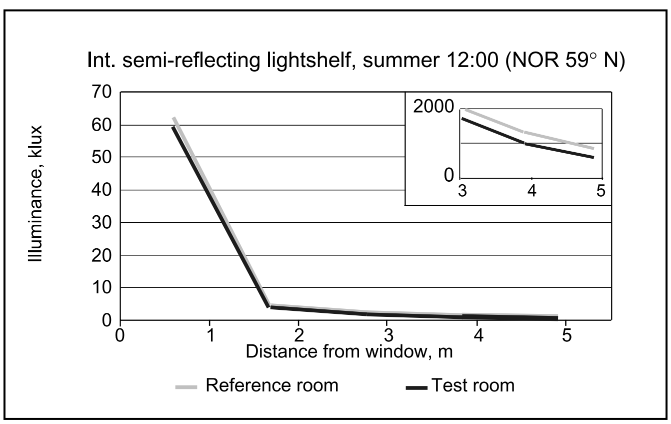
Overcast Sky

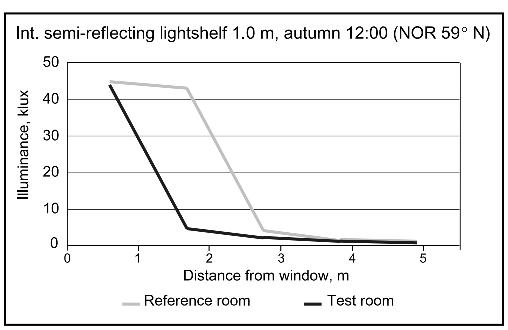
The internal light shelf reduces illuminance by 20% to 35% in the whole room. Even if the light shelf reduces the illuminance in the window zone, the daylight uniformity is not improved because the reduction is also considerable in the rest of the room.

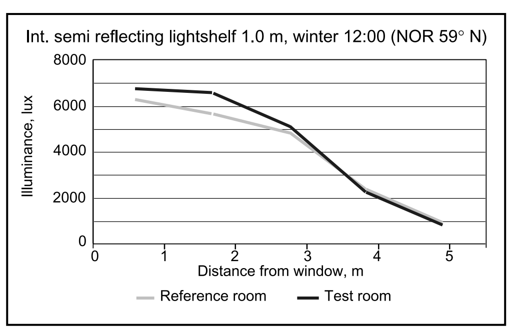


Clear Sky

Even at high sun angles in summer (53°), the light shelf does not protect areas near the window from direct sun. There is a small reduction in illuminance in the intermediate zone and a somewhat larger reduction in the rear wall zone (10–20%). In the spring and autumn, the light shelf shades direct sun in the window zone, but it also reduces illuminance by about 25% in the rear wall zone. At very low sun angles in winter, the illuminance increases in the window zone, probably because of inter-reflections between the desk and the underside of the light shelf (made of the same material as the upper side of the shelf). The light shelf does not increase the illuminance in the rear wall zone.







Conclusion (B)

The internal light shelf with semi-reflective surface does not increase the uniformity of daylight distribution in the room and it does not protect the window zone from direct sun. At low sun angles, an additional shading device is necessary to avoid glare problems. A deep horizontal light shelf installed just above head level may often also cause architectural or esthetic problems.

C. Interior Light Shelf with Semi-Transparent Surface (Norway)

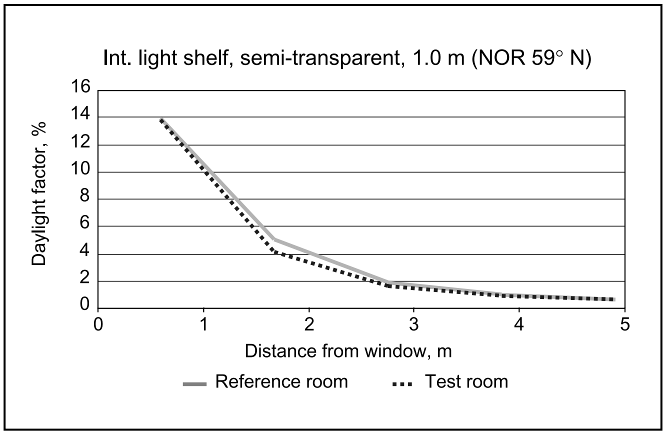
The Norwegian University of Science and Technology tested an interior horizontal light shelf 1.0 m deep, the full width of the window, and mounted between a clerestory window (1.0 m^2) and a view window (2.2 m^2). The light shelf is made of solar control glazing (Pilkington Kappa Sol Reflecta, now known as Pilkington Eclipse: light transmission 33%, reflection 43% or 50% depending on mounting), which gives the light shelf a semi-transparent surface. The reference room had clear, unshaded glazing of equal size to the test room. Measurements were made in an occupied office building at Sandvika, Norway (near Oslo) at latitude 59°N. See detailed test room description in Appendix 8.4.

Light Shelf - Interior (1.0 m deep) **Norway: 59°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal - Overcast (DF%)	4.2%	5.0%	1.6%	1.9%	0.7%	0.7%	5.9	2.4
Horizontal - Clear winter: Noon	Sun	Sun	Sun	Sun	Sun	Sun	18.7	69.9
Horizontal - Clear equinox: Noon	Sun	Sun	2,330	1,930	1,110	970	68.5	90.7

Note: The window, intermediate, and rear zone sensors were 1.67, 2.75, and 4.91 m from the window, respectively. "Sun" indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

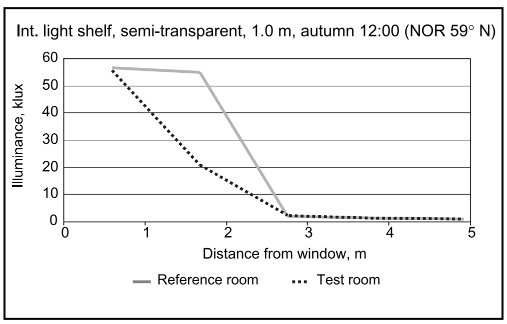
Overcast Sky

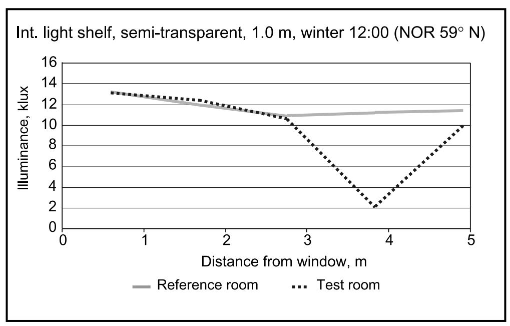
The internal light shelf reduces illuminance by about 15% in the intermediate zone. In the rear wall zone, the illuminance is equal to that observed in the reference room. The luminance difference is large in the area close to the window, and the daylight distribution in the window zone has a greater gradient in the test room than in the reference room.



Clear Sky

In spring or autumn, the light shelf shades an area near the window from direct sunlight, and the illuminance in the intermediate and rear wall zone is somewhat increased (10–20%). At very low sun angles, the internal light shelf does not shade or redirect direct sunlight. The whole work plane is exposed to direct sunlight.



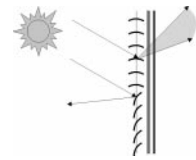


Conclusion (C)

The internal light shelf with semi-transparent surface does not increase the uniformity of daylight distribution in the room. At equinox, the light shelf may shade an area near the window from direct sunlight, but at low sun angles an additional shading device is necessary to avoid glare problems. A deep horizontal light shelf installed just above head height may often also cause architectural or aesthetic problems.

Figure 4-3.8: interior view of the test room with a semi-transparent, interior light shelf on an overcast winter day

4.4. Louvers and Blind Systems



Louvers and blinds are classic daylighting systems that can be applied for solar shading, to protect against glare and to redirect daylight.

4.4.1. Technical Description

Components

Louvers and blinds are composed of multiple horizontal, vertical, or sloping slats. There are various kinds of louver and blind systems, some of which make use of highly sophisticated shapes and surface finishes. Many of these specific types of systems are described below following a general description of conventional louvers and blinds.

Production

Exterior louvers are usually made of galvanised steel, anodised or painted aluminium, or plastic (PVC) for high durability and low maintenance. Interior venetian blinds are usually made from small- or medium-sized PVC or painted aluminium. The slats can be either flat or curved. Slats are usually evenly spaced at a distance that is smaller than the slat width so that the slats will overlap when fully closed. Slat size varies with the location of the blinds: exterior, interior, or between the panes in a double-paned window. Exterior slats are usually between 50 and 100 mm wide; interior slats are usually 10 to 50 mm wide.

Location in Window System

Louvers or blinds can be located on the exterior or interior of any window or skylight, or between two panes of glass. Louvers are generally situated on the exterior of the facade; blinds are fitted inside or between glazing.

Technical Barriers

Depending on slat angle, louvers and blinds partly or completely obstruct directional view to the outside. Vertical blinds allow a vertical view of the sky dome, and horizontal blinds reduce the vertical height of the exterior view. An occupant’s perception of view can sometimes be obstructed by the small-scale structure of slats, which generates visual confusion as the eye sorts out the outside view from the blind itself. Many louvers and blinds are therefore designed to be fully or partially retracted.

Under sunny conditions, blinds can produce extremely bright lines along the slats, causing glare problems. With blinds at a horizontal angle, both direct sunlight and diffuse skylight can increase window glare due to increased luminance contrast between the slats and adjacent surfaces. Tilting the blinds upward increases glare as well as visibility of the sky; tilting the blinds downward provides shading and reduces glare problems. Glossy, reflective blinds may generate additional glare problems because sun and skylight may be reflected off the slat surface directly into the field of view. Some of these problems can be reduced by use of a diffuse slat surface.

4.4.2. Application

Louvers and blinds can be used in all orientations and at all latitudes and can be added to a window system whenever necessary. Exterior blinds affect the architectural and structural design of a building; interior blinds have less impact. In practise, horizontal louvers and blinds are generally used on all building orientations, and vertical blinds are predominantly used on east- and west-facing windows. Advanced designs have different requirements from conventional blinds.

4.4.3. Physical Principles and Characteristics

Louvers and blinds may obstruct, absorb, reflect and/or transmit solar radiation (diffuse and direct) to a building's interior. Their effect depends on the position of the sun and their location (exterior or interior), slat angle, and slat surface reflectance characteristics. Thus, the optical and thermal properties of a window with louvers or blinds are highly variable. Horizontal blinds in a horizontal position can receive light from the sun, sky, and ground. Upward-tilted slats transmit light primarily from the sun and sky, and downward-tilted slats transmit light primarily from the ground surface. Both louvers and blinds can increase penetration of daylight from direct sunlight. When skies are overcast, louvers and blinds promote an even distribution of daylight.

Fixed and Operable Louvers and Blinds

Fixed systems are usually designed for solar shading, and operable systems can be used to control thermal gains, protect against glare, and redirect daylight. On sunny days, downward-tilted slats will produce efficient shading of sunlight, but, under cloudy conditions, a fixed system may cause an unfavourable shading effect that significantly reduces indoor daylight. Movable systems need to be fully or partially retracted to operate optimally according to outdoor conditions. Depending on slat angle, slat surface treatment, and the spacing between slats, both sunlight and skylight may be reflected to the interior.

Translucent Blinds

Translucent blinds transmit a fraction of light when closed. Translucent vertical blinds are typically 100 mm wide and require little or no cleaning. Translucent blinds can be made of fabric, plastic, or perforated plastic material (typically offering various levels of light transmittance). If backlit, the blinds can act as a bright, large-area source of glare.

Light-Directing Louvers

There are many different types of light-directing or reflecting louvers, which generally consist of an upper surface of highly specular material that sometimes has perforations and concave curvature. Light-directing louvers are usually fitted between glazing and are typically 10–12 mm in width. These louvers have been designed to reflect the maximum possible amount of daylight to the ceiling while having a very low brightness at angles below the horizontal (Figures 4-4.1 and 4-4.2).

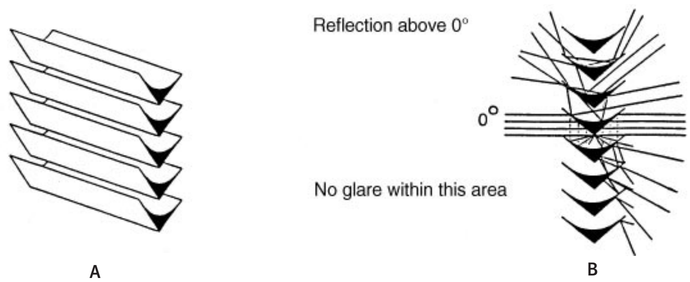


Figure 4-4.1: "Fish" system consisting of fixed horizontal louvers

The "Fish" system consists of fixed horizontal louvers with a triangular section that has been precisely aligned by special connections to the louver itself [Pohl and Scheiring 1998]. The system, designed only for vertical windows, is designed to limit glare and redirect diffuse light; additional shading is required (e.g., a roller blind) if heat gains and admission of sunlight are to be limited. The louvers are designed so that light from the upper quarter of the sky is transmitted to the upper quarter of the room (ceiling). Theoretically, the system without the glazing transmits 60% of diffuse light for an aluminium surface with 85% reflectance.

The "Okasolar" system, which is also a fixed system, consists of numerous equally spaced, three-sided, reflective louvers placed inside a double glazed unit. The system reflects light up towards the ceiling in the winter and has a shading effect in the summer. These blinds are designed to suit the latitude where they will be used.

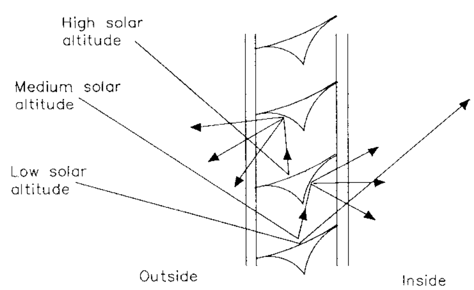


Figure 4-4.2: The Okasolar system consists of fixed, equally spaced, reflective louvers

4.4.4. Control

Louvers and blinds can be operated either manually or automatically. Automatically controlled louvers and blinds can increase energy efficiency, if controlled to reduce solar gain and admit visible daylight during daily and seasonal variations in solar position. However, automatic systems can produce discomfort in occupants who dislike the feeling of not having personal control over the system. Manually operated systems are generally less energy-efficient because occupants may or may not operate them "optimally" (e.g., operation may be motivated by glare or view, or systems may be left in position when the occupant is absent from the room). Research has found that occupant-preferred positions for louvers and blinds are relatively independent of daily, seasonal, and sometimes climatic conditions. Some studies have found a link between climate and the preferred positions for louvers and blinds [Rubin et al. 1978, Rea 1984, Inoue et al. 1988].

4.4.5. Maintenance

Maintenance of louvers and blinds can be difficult, especially when they have reflective slats. Interior slats collect dust; exterior slats can accumulate dirt and snow. Between-pane systems have an advantage of requiring little cleaning and are not as susceptible to damage (e.g., bending) as interior and exterior systems.

4.4.6. Cost and Energy Savings

Under sunny conditions, some systems can increase daylight penetration, reduce cooling loads, and make the variation more uniform between the brighter area near the window and darker interior zone. Cost and energy savings result from the more efficient use of light without added solar heat gains and cooling loads. For cloudy conditions, louver and blind systems can be energy-efficient if operated properly because most systems will provide less interior light than would be admitted by clear, unobstructed glazing. With reflective louver systems (e.g., those placed in the upper portion of a window to avoid reflected glare), illuminance levels can be increased under cloudy and sunny conditions when the sun is near-normal to the window.

4.4.7. Some Examples of Use

- Gartner Office Building, Gundelfingen, Germany: external mirrored blinds
- Riehle Office Building, Reutlingen, Germany: reflective louvers/blinds
- NMB Bank, Amsterdam, The Netherlands: reflective louvers
- Swanlea Secondary School, Whitechapel, London, UK: mirrored louvers
- Hooker Chemical Headquarters (offices), Buffalo, New York, USA: movable louvers
- Environmental Office of the Future, Watford, UK: motorised glazed louvers (Figure 4-4.3 and IEA SHC Task 21 *Daylight in Buildings: 15 Case Studies from Around the World*)
- Goetz Building, Wuerzburg, Germany: automated louver blinds

Figure 4-4.3: Motorised glazed louvers in the Environmental Office of the Future in Watford, UK

4.4.8. Simulations and Measured Results

One type of fixed louvers and five types of venetian blinds were tested.

A.	Standard light grey venetian blinds	**UK**
B.	Static and automated venetian blinds	**USA**
C.	Translucent venetian blinds	**UK**
D.	Fixed louvers–Fish system	**Austria**
E.	Inverted semi-silvered venetian blinds	**UK**
F.	Inverted semi-silvered translucent venetian blinds	**Denmark**

A. Standard, Light Grey Venetian Blinds (United Kingdom)

The Building Research Establishment, United Kingdom (UK), tested conventional 38-mm venetian blinds with a light grey finish. The blind system was monitored at three slat angle positions (fully closed, horizontal, and 45° downward tilted) in a south-facing mock-up office. The reference room was identical to the test room, but had unshaded, clear glazing.

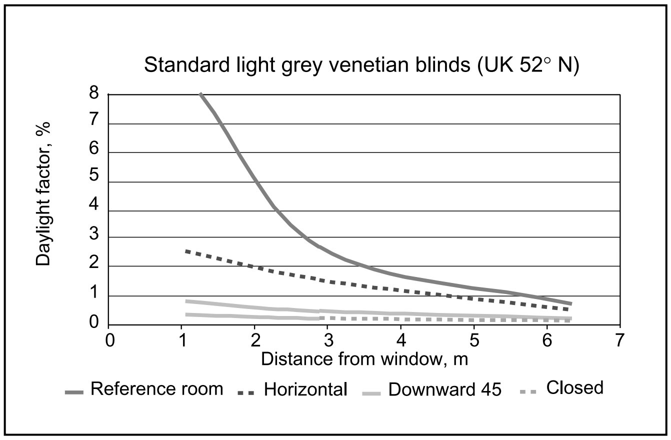
Interior light grey venetian blinds **UK: 52°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	2.5 %	9.1 %	1.5 %	2.9 %	0.5 %	0.7 %	9.5	3.8
Downward 45° - Overcast (DF%)	0.8 %	8.7 %	0.4 %	2.5 %	0.1 %	0.7 %	6.6	2.7
Closed 90° - Overcast (DF%)	0.3 %	8.9 %	0.1 %	2.7 %	≈ 0.0 %	0.7 %	8.7	2.8
Horizontal 0° - Clear winter: Noon	Sun	Sun	Sun	Sun	1,110	1,500	30.2	74.9
Horizontal 0° - Clear winter: 15:00	1,230	1,780	830	1,050	320	420	8.1	20.3
Downward 45° - Clear winter: Noon	530	Sun	270	Sun	130	1,360	25.0	65.2
Downward 45° - Clear winter: 15:00	210	1,890	100	1110	40	410	8.5	21.6
Closed 90° - Clear winter: Noon	150	Sun	70	Sun	30	1,520	25.7	71.7
Closed 90° - Clear winter: 15:00	70	2,380	30	1,460	10	560	8.9	28.1
Horizontal 0° - Clear equinox: Noon	1,800	3,290	980	1,540	470	740	68.9	79.7
Horizontal 0° - Clear equinox: 15:00	1,360	2,890	730	1,380	350	640	47.3	60.7
Downward 45° - Clear equinox: Noon	210	2,430	90	1,150	30	550	76.4	81.7
Downward 45° - Clear equinox: 15:00	170	2,590	70	1,250	20	560	28.9	17.5
Closed 90° - Clear equinox: Noon	60	1,470	30	560	10	270	37.6	21.4
Closed 90° - Clear equinox: 15:00	60	1,540	30	700	10	320	25.4	20.2
Horizontal 0° - Clear summer: Noon	1,210	2,170	630	950	280	410	84.3	65.5
Horizontal 0° - Clear summer: 15:00	970	2,010	510	900	230	380	61.1	50.9
Downward 45° - Clear summer: Noon	660	2,400	350	1040	160	440	80.4	65.9
Downward 45° - Clear summer: 15:00	550	2,140	290	950	130	410	60.5	51.3
Closed 90° - Clear summer: Noon	160	2,180	70	940	20	410	87.3	59.0
Closed 90° - Clear summer: 15:00	130	1,860	60	820	20	360	64.5	43.7

Note: For overcast sky measurements, the window, intermediate, and rear zone sensors were 1.05, 2.89, and 6.34 m from the window, respectively. For clear sky measurements, the window, intermediate, and rear zone sensors were 2.7, 4.5, and 8.1 m from the window, respectively. The tilt angle is defined as the vertical angle from horizontal where a positive angle is downwards, with a view of the ground from inside the building. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

Overcast Sky

The daylight factor on the work plane for standard grey venetian blinds was measured at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements were made for 3 days in the reference room and then averaged.

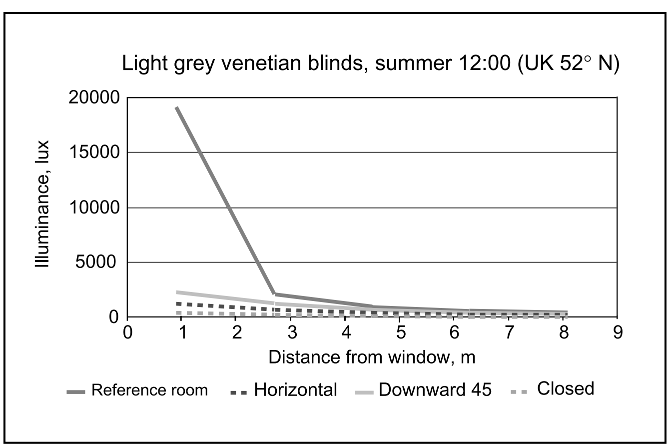
The conventional venetian blinds with a light grey finish in a horizontal slat angle position produced moderate, uniform variation in light between the window area and at the back of the room. The amount of light entering the room was reduced considerably in all cases, even when the slats were in horizontal position.

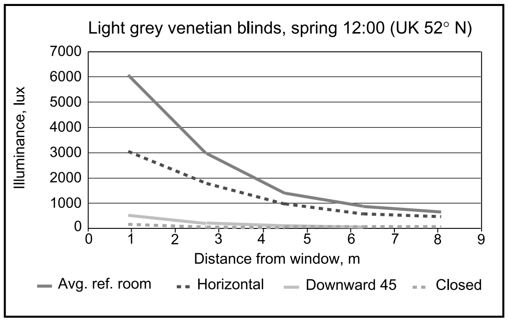


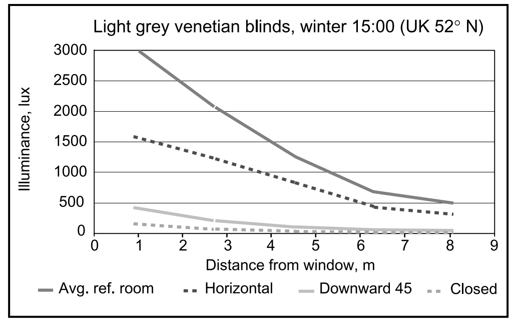
Clear Sky

The illuminance level was measured on the work plane for standard grey venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over 3 days in the reference room were averaged to illustrate the magnitude in illuminance level.

At high sun positions the blind inhibited sunlight from entering the room and reduced the difference in illuminance levels between the window area and the rest of the room. At low sun position, the slats in horizontal position reflected the sunlight into the interior, increasing the illuminance considerably compared to the effect of the downward-tilted position.







Conclusion (A)

For conventional venetian blinds, there is no advantage for glare control in closing the slats beyond 45°, and there are significant disadvantages in terms of room illuminance levels. A design improvement would therefore be to limit the degree to which such blinds would close under normal operation while allowing users the option of completely closing the blinds if necessary under other conditions.

B. Static and Automated Venetian Blinds (USA)

The Lawrence Berkeley National Laboratory, USA, tested interior, semi-specular, white painted aluminium venetian blinds (17 mm wide, spaced 15 mm apart) in two identical rooms. The primary purpose was to test the performance of the control system; the daylighting performance of these blinds has been tested at other institutions.

In the test room, the slat tilt angle was automatically controlled to maintain interior daylight levels at 500 lux throughout the day (the venetian blinds were never retracted). In the reference room, a static blind angle was set to remain the same during the day: either horizontal (0°) or 45° downward tilted (view of ground from the interior). The rooms were oriented 62.6° east of south with partially obstructed views of nearby high-rise buildings. The windows spanned the full width of the room and had a head height of 2.58 m and a sill height of 0.78 m.

Interior static and automated venetian blinds **USA: 37°N** Monitoring case and time	Interior Illuminance Level (lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Auto 0°, Static 0° - Overcast (DF%)	NA	NA	NA	NA	NA	NA	4.2	NA
Auto 0°, Static 0° - Clear winter: 9:00	450	560	320	380	220	260	28.0	NA
Auto 48°, Static 0° - Clear winter: Noon	960	2,100	690	1510	420	990	57.0	
Auto 0°, Static 0° - Clear winter: 15:00	310	320	250	250	220	210	28.8	
Auto 70°, Static 0° - Clear equinox: 9:00	1,630	5,300	1150	3,360	720	2,010	43.2	NA
Auto 67°, Static 45° - Clear equinox: 9:00	2,030	2,420	1,460	1,790	960	1,210	53.0	
Auto 52°, Static 0° - Clear equinox: Noon	1,030	1,700	730	1,250	430	830	72.7	
Auto 48°, Static 45° - Clear equinox: Noon	900	1,020	660	760	390	460	74.9	
Auto 0°, Static 0° - Clear equinox: 15:00	420	400	350	340	290	290	53.5	
Auto 0°, Static 45° - Clear equinox: 15:00	390	160	330	130	290	100	51.5	
Auto 65°, Static 0° - Clear summer: 9:00	1,340	4,430	900	2,930	540	1,630	78.3	NA
Auto 67°, Static 45° - Clear summer: 9:00	1,560	1,660	1,090	1,180	690	750	64.6	
Auto 43°, Static 0° - Clear summer: Noon	750	1,130	550	840	320	570	106.0	
Auto 26°, Static 45° - Clear summer: Noon	790	690	610	510	400	280	86.1	
Auto 0°, Static 0° - Clear summer: 15:00	540	580	470	510	430	460	84.3	
Auto 0°, Static 45° - Clear summer: 15:00	510	220	440	180	380	120	67.5	

Note: The measured data in the test room column are for the automatically controlled blind; data in reference room column are for the static blind in a fixed slat angle position (e.g. Auto 0°, Static 0° means that both the automatic and static blind were in a horizontal position). The window, intermediate, and rear zone sensors were 1.5, 2.4, and 4.3 m from the window, respectively. The tilt angle is defined as the vertical angle from horizontal where a positive angle is downward, with a view of the ground from inside the building. Evg (klux) is global exterior horizontal illuminance. Evgs is not available (NA).

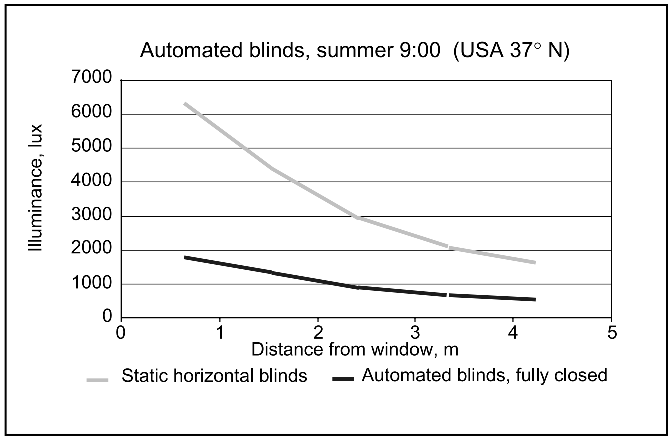
Overcast Sky

There were no comparative measurements taken under overcast sky conditions. Therefore, no conclusions were drawn for these conditions.

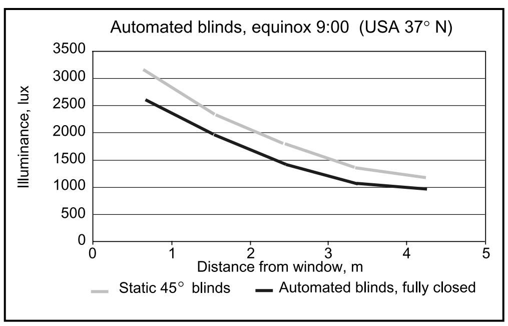
Clear Sky

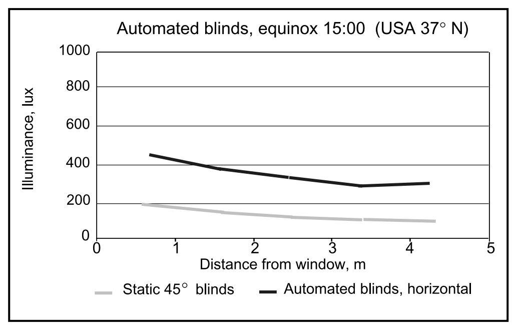
The Auto venetian blinds are more effective than both the horizontal (0°) and 45° static blinds at maintaining daylight illuminance levels at the specified design level of 500 lux. In the summer, the Auto venetian blind in a fully closed position yields more uniform maintained illuminance levels (540–1,340 lux) throughout the test room compared to the reference room with horizontal blind (between 1,630–4,430 lux). No redirection of light can be noted in the illuminance profile.

For the equinox, the same conclusions can be made as for the summer solstice period except that the magnitude of the difference in illuminance between the test and reference rooms is smaller because of decreased daylight availability.



Because the test rooms faced east-southeast, sunlight does not hit this facade in the afternoon. In this situation, the Auto venetian blinds at a horizontal tilt angle provide more daylight than partly closed blinds. Illuminance profiles for the two situations are given in the figures below at 9:00 and 15:00 respectively, for the same day.





Conclusion (B)

Auto control of venetian blind systems may perform well in all climates. However, the automatic control algorithm may need to be adjusted to accommodate the unique cooling- or heating-load-to-daylighting balance for the building location. For low-latitude countries in hot climates, the system may be more energy-efficient if controlled to provide less overall transmitted solar radiation or if placed on the exterior of the building. For high-latitude countries in cold climates, the system may be more energy-efficient if controlled to provide more daylight and solar radiation.

The test results show that it is important to control the blinds in response to available daylight. However, additional control to avoid glare from the exterior or from the blinds themselves was not investigated. Algorithms have been developed to reduce movement of blinds under partly cloudy conditions, but this should be packaged as a user-defined option to ensure occupant satisfaction.

C. Translucent Venetian Blinds (United Kingdom)

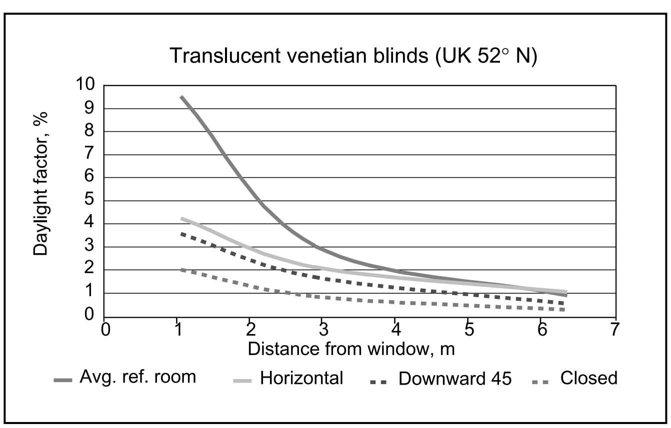
The Building Research Establishment, United Kingdom (UK), tested 25-mm-wide white translucent blinds with a transmission of less than 5%. The blind system was monitored (winter and equinox) at three slat angle positions (fully closed, horizontal, and 45° downward tilted) in a south-facing mock-up office. The reference room was identical to the test room, but had unshaded, clear glazing.

Interior translucent blinds UK: 52°N Monitoring case and time	Interior Illuminance level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	3.6 %	9.0 %	1.7 %	2.9 %	0.5 %	0.7 %	19.6	7.8
Downward 45° - Overcast (DF%)	4.2 %	10.4 %	2.1 %	3.2 %	1.0 %	1.3 %	3.6	1.5
Closed 90° - Overcast (DF%)	2.0 %	8.9 %	0.8 %	2.7 %	0.3 %	0.7 %	8.5	3.4
Horizontal 0° - Clear winter: Noon	3,120	3,920	Sun	Sun	1,110	1,500	29.4	71.3
Horizontal 0° - Clear winter: 15:00	2,100	2,910	1,350	1,690	570	730	12.8	35.8
Horizontal 0° - Clear equinox: Noon	2,790	4,070	1,380	1,500	640	750	55.5	86.5
Horizontal 0° - Clear equinox: 15:00	2,310	3,530	1,150	1,760	520	790	35.1	66.5
Downward 45° - Clear equinox: Noon	1,810	2,390	930	1,130	460	570	77.1	77.4
Downward 45° - Clear equinox: 15:00	1,410	2,550	720	1,220	360	580	56.8	63.2
Closed 90° - Clear equinox: Noon	250	4,450	250	1,700	40	780	NA	NA
Closed 90° - Clear equinox: 15:00	200	3,300	90	1,440	20	640	NA	NA

Note: For overcast sky measurements, the window, intermediate, and rear zone sensors were 1.05, 2.89, and 6.34 m from the window, respectively. For clear sky measurements, the window, intermediate, and rear zone sensors were 2.7, 4.5, and 8.1 m from the window, respectively. The tilt angle is defined as the vertical angle from horizontal where a positive angle is downwards, with a view of the ground from inside the building. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

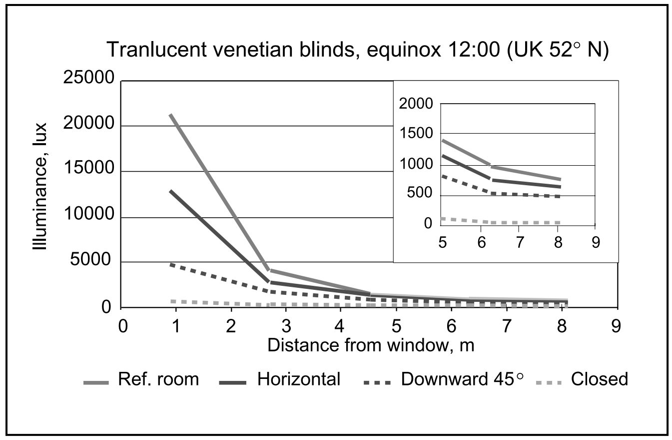
Overcast Sky

The daylight factors on the work plane for translucent venetian blinds are slightly higher than those measured for standard blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over three days in the reference room were averaged.



Clear Sky

Under sunny conditions, there are only small differences between the illuminance levels with translucent and standard blinds. The illuminance level on the work plane was measured for translucent venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over three days in the reference room were averaged to illustrate the magnitude in illuminance level in the reference room.



Conclusion (C)

In general, translucent blinds let in more daylight than traditional blinds. The concept of translucent blinds might offer the possibility of complete glare control while allowing more diffuse daylight into the space than is possible with other systems. However, care must be taken that the blinds themselves do not become a secondary glare source.

D. Fixed Louvers – Fish System (Austria)

The Bartenbach Lichtlabor, Austria (AUT), tested a combined system that consisted of two different daylighting components in the upper and lower areas of the window. The upper area had "Fish" louvers, a fixed, reflective light-directing system (see Figure 4-4.1). The lower area had exterior, movable light-directing louvers to permit glare control. The reference room had 45° downward-tilted exterior venetian blinds, with window area of equal size to the test room. The main purpose of these tests was to compare illuminance levels and light distribution when the overall average interior luminances of the two windows were the same (low levels, no glare).

Fish system - between glazing **Austria: 47°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	2.6 %	1.5 %	2.3 %	1.2 %	1.5 %	0.9 %	19.4	8.0
Clear equinox: Noon	470	290	430	220	280	150	89.7	62.8
Clear equinox: 15:00	440	310	390	230	260	160	87.6	63.6
Clear summer: 9:00	70	110	60	90	40	60	55.2	8.4
Clear summer: Noon	280	250	230	190	160	130	97.1	40.0

Note: The window, intermediate, and rear zone sensors were 1.3, 2.0, and 3.4 m from the window, respectively. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

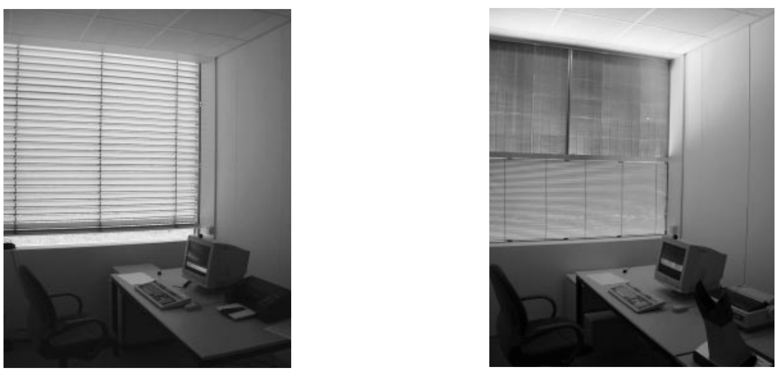
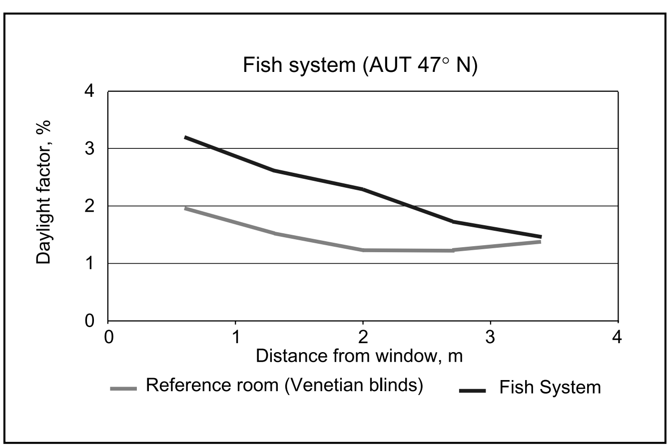


Figure 4-4.4: Interior view of test (right) and reference (left) rooms

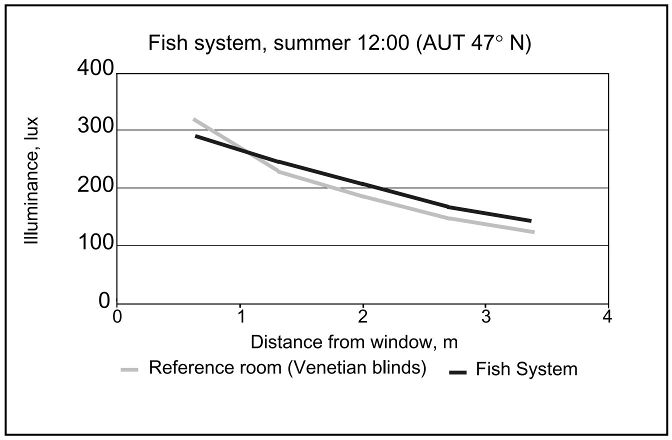
Overcast Sky

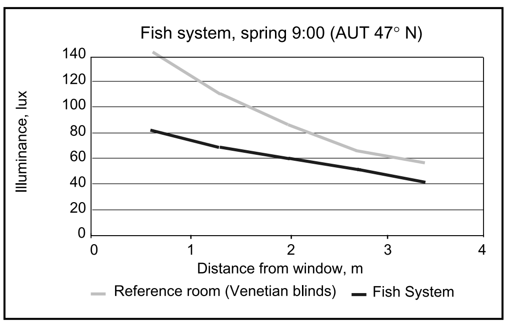
Measurements for the Fish system with an overcast sky showed almost twice the illuminance level in the whole room compared to that in the reference room with exterior downward-tilted venetian blinds. However, no measurements were made with clear, unobstructed glazing. Therefore care should be taken when comparing the results.

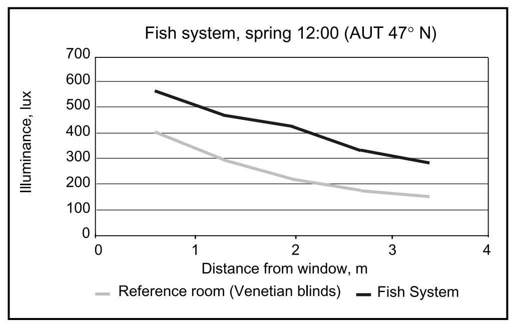


Clear Sky

Because the exterior blinds were partly closed, the overall illuminance levels were very low in both rooms. The clear sky summer measurements show a lower illuminance level for the test room in the morning but a higher illuminance level at noon. Light penetration appears to be highly dependent on the altitude and azimuth of the sun.







Conclusion (D)

The Fish system generally improves the illuminance distribution somewhat compared to ordinary, closed blinds. With the same window luminance level, higher work plane illuminance levels are achieved at high sun positions compared to those achieved by the reference system with exterior downward-tilted venetian blinds. It should be noted that the results only cover the combination of the Fish system with external blinds and only at very low internal illuminance levels. The Fish system was not investigated by itself.

E. Inverted Semi-Silvered Venetian Blinds (United Kingdom)

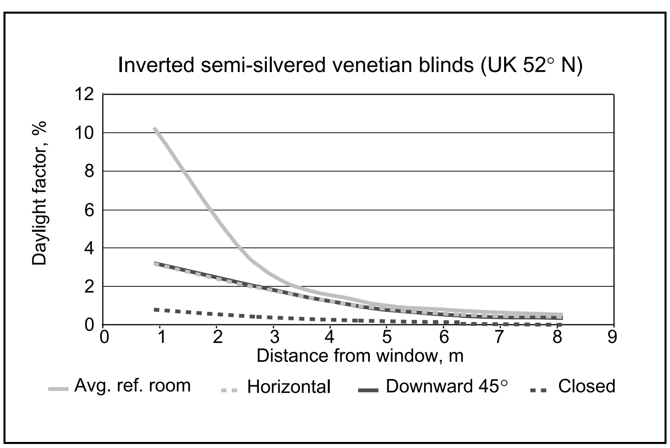
The Building Research Establishment, United Kingdom (UK), tested an experimental 38-mm-wide blind with the louvers inverted and painted silver on the upper (concave) side. The blind system was monitored (summer and equinox) at three slat angle positions (fully closed, horizontal, and 45° downward tilted) in a south-facing mock-up office.

Inverted semi-silvered blinds - Interior **UK: 52°N** Monitoring case and time	Interior Illuminance level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	1.9 %	3.2 %	1.0 %	1.3 %	0.4 %	0.5 %	15.0	6.2
Downward 45° - Overcast (DF%)	2.0 %	3.2 %	0.9 %	1.3 %	0.4 %	0.5 %	4.2	1.7
Closed 90° - Overcast (DF%)	0.4 %	3.0 %	0.2 %	1.2 %	0.1 %	0.5 %	14.2	5.7
Horizontal 0° - Clear equinox: Noon	2,840	3,190	1,490	1,510	690	730	56.3	85.4
Horizontal 0° - Clear equinox: 15:00	1,070	1,670	590	770	280	380	13.1	20.3
Downward 45° - Clear equinox: Noon	750	Sun	390	1850	190	960	42.6	78.9
Downward 45° - Clear equinox: 15:00	380	2,590	190	1150	90	470	16.3	35.0
Closed 90° - Clear equinox: Noon	30	1,060	10	640	4	380	13.6	11.7
Closed 90° - Clear equinox: 15:00	10	310	5	130	2	170	9.4	5.7
Horizontal 0° - Clear summer: Noon	1,720	2,070	850	900	380	440	87.3	57.1
Horizontal 0° - Clear summer: 15:00	1,200	1,850	610	830	290	400	68.9	45.2
Downward 45° - Clear summer: Noon	350	2,930	170	1,190	90	530	46.8	39.8
Downward 45° - Clear summer: 15:00	130	900	60	390	30	190	27.7	13.2
Closed 90° - Clear summer: Noon	230	2,590	110	1,090	40	490	86.9	56.3
Closed 90° - Clear summer: 15:00	180	2,030	80	890	30	400	61.2	40.2

Note: The window, intermediate, and rear zone sensors were 2.7, 4.5, and 8.1 m from the window, respectively. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

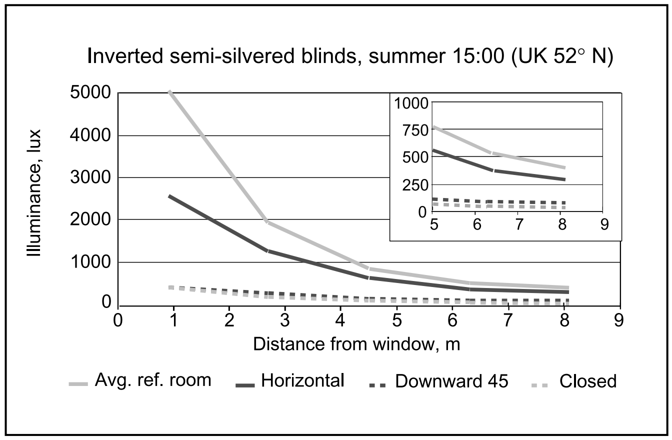
Overcast Sky

The daylight factor was measured on the work plane for inverted semi-silvered venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over three days in the reference room (clear glass) were averaged. The illuminances at 45° and horizontal are almost the same.



Clear Sky

Clear sky at 15:00: The illuminance level was measured on the work plane for inverted semi-silvered venetian blinds at three slat angle positions (horizontal, 45° downward tilted, and fully closed). Measurements taken over three days in the reference room were averaged to illustrate the magnitude in illuminance level. The horizontal slats allowed high illuminance levels (300–2,500 lux) while evening out the difference between the window zone and the rest of the room.



Conclusion (E)

Compared to conventional blinds, inverted silvered blinds give extra daylight when the slats are horizontal, especially at high sun angles (summer). Silvered blinds always involve potential glare problems and can normally only be used in a daylight window above eye height.

F. Inverted Semi-Silvered Translucent Venetian Blinds (Denmark)

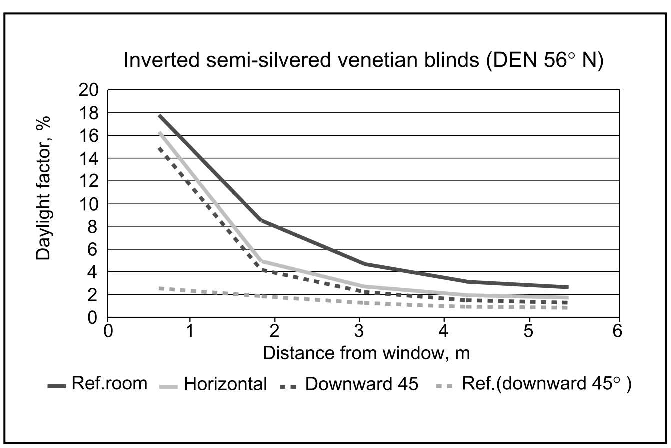
The Danish Building Research Institute, Denmark (DEN), tested a translucent, 50-mm venetian blind (made by Hüppe) with a transmission lower than 10%. The slats are inverted and silvered on the upper (concave) side and are light grey on the downward side. The blinds were monitored in summer, winter, and at equinox for two slat positions (horizontal and 45° downward tilted). The system was positioned above eye height for a standing person (1.8 m) with no supplementary system below this height. For clear sky measurements, the reference room was shaded by standard white venetian blinds tilted 45° down-ward and covering the entire window area. For overcast sky measurements, the reference room had a clear, unobstructed window.

Inverted semi-silvered blinds - Interior Denmark: 56°N Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Horizontal 0° - Overcast (DF%)	4.9 %	8.6 %	2.7 %	4.6 %	1.7 %	2.6 %	19.3	7.6
Downward 45° - Overcast (DF%)	4.1 %	8.5 %	2.2 %	4.7 %	1.3 %	2.7 %	7.5	3.0
Standard Downward 45° - Overcast (DF%)	1.8 %	8.5 %	1.3 %	4.7 %	0.8 %	2.7 %	7.5	3.0
Downward 45° - Clear winter: 9:00	5,480	2,070	2,320	1,290	1,670	900	8.7	38.2
Downward 45° - Clear winter: Noon	Sun	3,710	> 4,000	2,540	> 4,000	1,820	29.3	87.7
Horizontal 0° - Clear equinox: 9:00	5,640	2,410	3,650	1,610	2,310	1,070	40.4	67.6
Horizontal 0° - Clear equinox: Noon	7,830	3,360	> 4,000	2,280	3,730	1,540	66.9	94.0
Downward 45° - Clear equinox: 9:00	4,130	2,340	2,770	1,600	1,040	1,830	38.4	65.1
Downward 45° - Clear equinox: Noon	4,950	3,320	3,710	2,300	2,790	1,520	65.5	92.6
Horizontal 0° - Clear summer: 9:00	3,820	1,690	2,340	1,150	1,470	760	66.7	46.9
Horizontal 0° - Clear summer: Noon	5,650	2,540	3,710	1,720	2,320	1150	91.6	69.3
Downward 45° - Clear summer: 9:00	2,470	1,530	1,560	1,040	980	690	74.0	44.8
Downward 45° - Clear summer: Noon	3,480	2,380	2,330	1,620	1,440	1,083	98.7	65.8

Note: The window, intermediate, and rear zone sensors were 1.8, 3.0, and 5.4 m from the window, respectively. "Sun" indicates sunlight striking the sensors. ">4000" indicates that the sensors are at a state of saturation. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing 7° east of due south. DF% is the daylight factor.

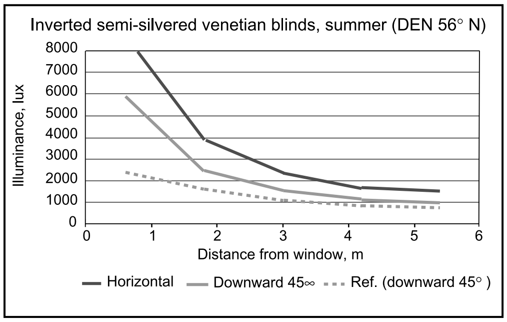
Overcast Sky

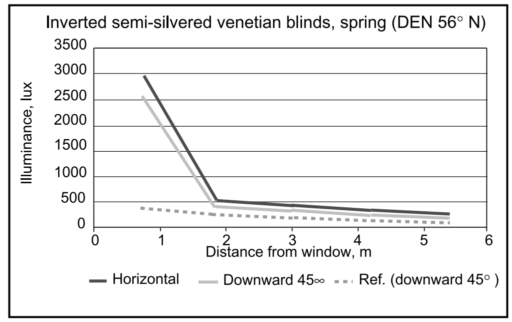
The blinds reduced the interior illuminance level on the work plane throughout the interior compared to the reference room with an unshaded window of equal size. The smallest light reduction occurred when the slats were in the horizontal position. However, for real-life applications, some additional shading for the view window will be necessary because the silvered blinds cause glare problems themselves if used below eye height. The lower curve is for the reference room with 45° downward-tilted blinds in full height of the window.



Clear Sky

Both in summer and at equinox, most of the reflected light illuminates the ceiling and increases light levels in the intermediate and rear wall zones of the room compared to the effect of a standard downward-tilted blind. Sunlight reflected to adjacent walls and ceiling can create visual disturbance, i.e., distracting, distorted patterns of light bands. Closing the blinds or using a different surface treatment may reduce this problem. The reference room has downward-tilted (45°) standard venetian blinds.

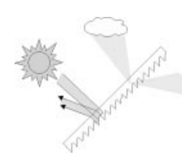




Conclusion (F)

The spacing between the slats is smaller than for standard blinds, which reduces the view to the outside even when the slats are in the horizontal position. However, because of the translucency of the blinds, some sense of connection with the outside is maintained when the blinds are tilted. The shape of the slats and reflecting surface treatment implies that the system should be implemented in a daylight window only in order to avoid glare problems. It will then perform similar to a mirrored louver system.

4.5. Prismatic Panels



Prismatic panels are thin, planar, sawtooth devices made of clear acrylic that are used in temperate climates to redirect or refract daylight. When used as a shading system, they refract direct sunlight but transmit diffuse skylight. They can be applied in many different ways, in fixed or sun-tracking arrangements, to facades and skylights.

4.5.1. Technical Description

Components

A linear prismatic panel consists of an array of acrylic prisms with one surface of each prism forming a plane surface known as the prism backing. There are two refracting angles. Very often these prismatic systems are inserted in a double-glazed unit to eliminate maintenance.

Production

Currently, two different manufacturing processes are used to make prismatic panels:

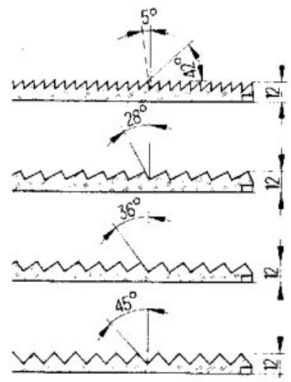


Figure 4-5.1: Four types of commercially available prismatic panels

Injection moulding. Prismatic panels are produced from acrylic polymer in four different configurations (different refracting angles). Some panels are partially coated with an aluminium film with high specular reflectance on one surface of each prism.

Specialised etching. This etching process produces prisms that are spaced less than a millimeter apart. The resulting acrylic film is lightweight yet still has good optical properties. This film can be applied on the inside of a double-glazed unit.

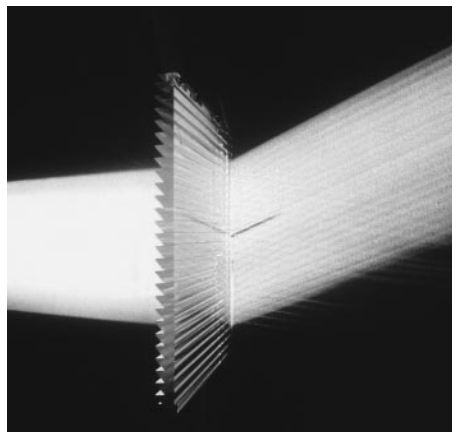


Figure 4-5.2: Cross-section of a linear prismatic panel and visualisation of the light redirection achieved by the panel

Location in Window System

Prismatic panels are used in fixed and movable configurations. Depending on the daylighting strategy being used, they can be positioned in the window pane (fixed configuration) on the exterior and/or interior side. The panels offer a transparent but distorted view to the outside. An extra view window will usually be needed unless the panel can open to allow a view.

Prismatic panels have two very different functions: a) solar shading, and b) redirection of daylight. Their location in relation to the facade or the roof is very dependent on the specific application.

Technical Barriers

If prismatic panels are used as sun-shading devices in a fixed configuration, additional components are needed to prevent colour dispersion. These could include, for example, an etched sheet of glass (slightly diffusing) behind the system.

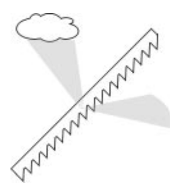
If used for redirecting sunlight, currently available prismatic panel designs may redirect some sunlight downward, causing glare. Computer analysis shows that for a vertical, fixed prismatic panel, some downward sunlight is inevitable at some times of the year. With correct profile and seasonal tilting, these downward beams can be avoided, however.

Historically, the effect of prismatic panels on daylight has been well known. There are patents on this technology dating from the beginning of the 20th century. However, production was a significant barrier in the past. With the advent of acrylic polymer, it became possible for the first time to produce very precise panels. In addition, covering single surfaces of a prism with reflective coatings has expanded the possibilities of prismatic systems. Still, cost is an important barrier to the panels' wider use.

The panels' high coefficient of expansion usually requires that they be designed to allow for thermal expansion. Since acrylic burns, fire regulations must be checked when prismatic panels are used.

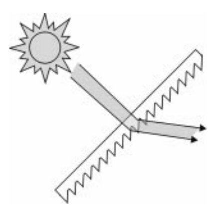
4.5.2. Application

As a light-directing system, prismatic panels can be used to guide diffuse daylight or sunlight.



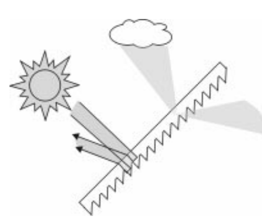
Diffuse Daylight

Prismatic panels are normally used in the vertical plane of the facade to redirect light from the outside sky to the upper half of the inside room, usually the ceiling. Simultaneously, the panels reduce the brightness of the window. With this profile, the panels operate best as an anti-glare system with a simultaneous light-directing function. For sunny facades, however, additional sun shading is necessary in front of the panels.



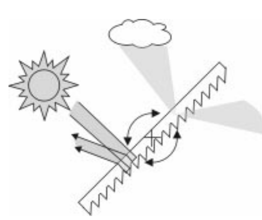
Sunlight

Prismatic panels can also be used to direct sunlight into a room. To prevent glare and also colour dispersion, the correct profile and a seasonal tilting of the panels are essential. See Section 4.5.8 for test room studies at the University of Sydney, Australia.



Fixed Sun-Shading System

This application is usually found in glazed roofs. The prismatic structure is designed according to the movement of the sun, and the panels are integrated into a double-glazed unit. See Section 4.5.8 for measurements made at Bartenbach LichtLabor, Austria.



Moveable Sun-Shading System

For this application, prismatic panels are used in louver form. They are placed in front of or behind double glazing, in a vertical or horizontal arrangement (a double glazed unit is no longer necessary). This application will control glare from the sun but not the sky; in other words, it acts only as a sun-shading device.

4.5.3. Physical Principles and Characteristics

The main function of light-directing prismatic glazing is to achieve deep penetration of natural light. The prismatic panel uses both reflection and refraction to enable the controlled use of daylight in buildings. The system can be designed to reflect light coming from a certain range of angles while transmitting light coming from other angles. Refraction and total internal reflection (based on the critical angle of the material) can be used to change the direction of transmitted light rays. The fractions of reflected and refracted light depend on the angle of incidence, the indices of refraction, and the state of polarisation of the incident light.

For deep penetration of sunlight, a prismatic panel must accommodate a wide range of solar altitudes. The refracted light should emerge at an angle less than 15° above the horizontal to obtain maximum penetration without creating descending rays of sunlight that create glare. The panel's performance is therefore determined by an appropriate configuration of the refracting angles. A specific configuration for the prismatic profile is usually required for different geometric and geographic situations, to achieve high illuminance levels at the back of a room. In addition, a good surface texture with a high reflectivity is required for the ceiling, especially in the area near the window and for approximately one-third of the ceiling depth.

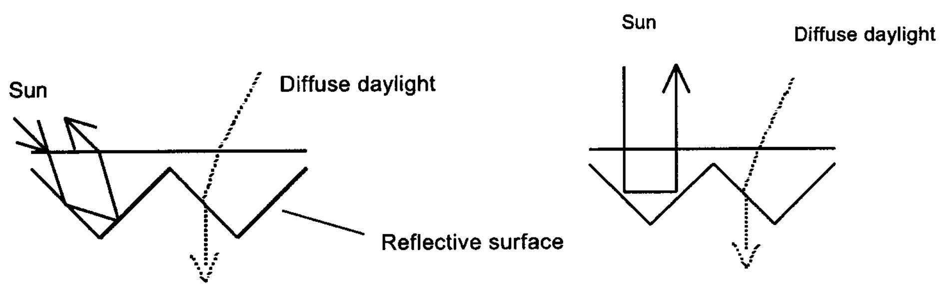


Figure 4-5.3: Behaviour of direct and diffuse components of daylight in a fixed prismatic sun-shading device (left) and in a movable prismatic sun-shading device (right). The phenomenon of total internal reflection is used to reflect the sun's rays

4.5.4. Control

When prismatic panels are applied as a movable sun-shading system, one-axis automatic tracking of the panels according to the movement of the sun is generally required. For many light-redirection applications, only seasonal adjustments are needed.

4.5.5. Maintenance

Prismatic panels inside a double-glazed unit do not require any maintenance other than the normal washing of the exterior and interior glazing surfaces. If the panels are exposed, they must be very carefully cleaned so as not to damage the optical surfaces.

4.5.6. Cost and Energy Savings

Costs for a prismatic panel alone are in the range of 200 euros (for high-volume production) to 400 euros (for low-volume production) per square metre. The cost of prismatic film is 40 to 80 euros per square metre. Potential energy savings can be derived from the measurement results in Chapter 4.5.8.

4.5.7. Some Examples of Use

- 3M Centre, Building 275, St. Paul, Minnesota, USA: light guides and light emitters made from prismatic film
- 3M Office Building, Austin, Texas, USA: rooflight reflectors fitted with prismatic film at the top of the atrium

Figure 4-5.4: SBV, Biel, Switzerland. The structure in front of the glass curtain wall, one storey above ground level, supports movable prismatic panels. Behind these panels, there are also light-directing prismatic panels

Figure 4-5.5: Sparkasse, Bamberg, Germany. Fixed sun-shielding and light-redirecting prismatic panels inside double glazing

Figure 4-5.6: German Parliament Building, Bonn, Germany. Movable sun-shading prismatic panels

4.5.8. Simulations and Measured Results

Test room data following the IEA Task 21 monitoring protocol are given for Norway and Germany. The remaining abbreviated results are given with references, as appropriate.

A.	Prismatic panel at vertical clerestory window	**Norway**
B.	Prismatic panels combined with inverted, semi-perforated blinds in a vertical window	**Germany**
C.	Light-directing and sun-shading prismatic panels	**Austria**
D.	Prismatic film and prismatic panel	**United Kingdom**

A. Prismatic panel (Norway)

Measurements of prismatic panels (Siteco 45°) were made by the Norwegian University of Science and Technology, Norway (NOR). The test rooms were 2.9 m wide, 5.5 m deep, and 2.7 m high. The test room window was separated into two: a full-width clerestory (1.0

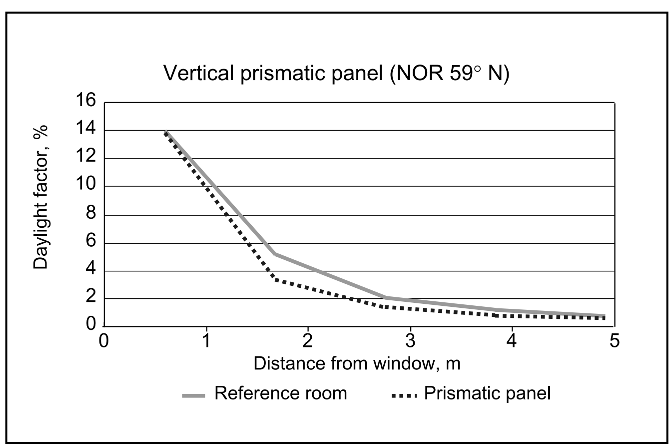
m²) above a view window (2.2 m²). Prismatic panels were mounted vertically between the two panes of the clerestory. The prismatic panel occupied 31% of the total glazing area. The reference room had clear, unshaded glazing. Results are presented for the case when the sun is perpendicular to the window facade. Measurements were made in an occupied office building at Sandvika, Norway (near Oslo) at latitude 59°N. For a detailed description of the test rooms, see Appendix 8.4.

Prismatic Panel **Norway: 59°N** Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	3.4%	5.2%	1.4%	2.1%	0.6%	0.7%	3.4	1.4
Clear winter: Noon	Sun	Sun	Sun	Sun	Sun	Sun	11.0	51.1
Clear equinox: Noon	Sun	Sun	Sun	Sun	1,410	1,640	38.4	90.8
Clear summer:Noon	3,240	3,130	2,140	1,650	710	660	87.5	76.0

Note: The window, intermediate, and rear zone sensors were 1.67, 2.75, and 4.91 m from the window, respectively. "Sun" indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

Overcast Sky

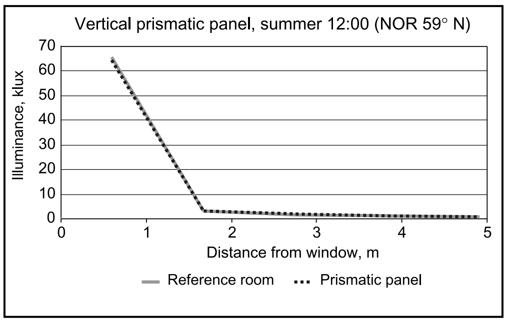
Under overcast sky conditions, the prismatic panels reduced the illuminance in all zones by 20–35%; daylight distribution was less uniform than in the reference room. The brightness of the upper part of the window was reduced.

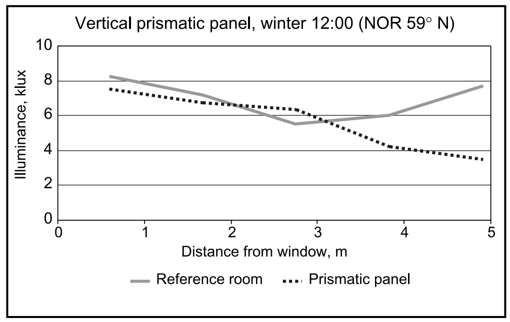


Clear Sky

For summer clear sky conditions, the prismatic panels provided more uniform daylight distribution in the room than under overcast skies. The illuminance in the intermediate zone was increased by up to 30%; in the rear wall zone, the average increase was about 14%.

In the reference room at low sun angles during the equinox and winter solstice, direct sunlight penetrated the entire depth of the room at low sun angles; in the test room, the prismatic panels reduced or prevented direct sun from reaching the rear wall zone. Consequently, the luminance differences in the rear zone of the test room were evened out. The prismatic panels also prevented direct sun dazzle for people first entering the room.





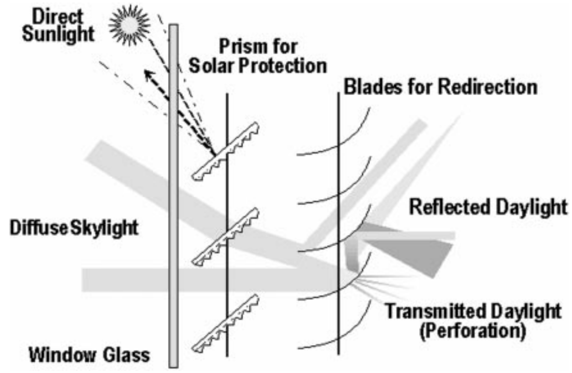
Conclusions (A)

Prismatic panels have limited applications in climates dominated by overcast sky conditions. For clear sky climates, the panels can direct sunlight into a room and provide a relatively uniform daylight distribution.

B. Prismatic Panels Combined with Inverted, Semi-Perforated Blinds (Germany)

Measurements of a Siteco 45/45 prismatic panel combined with a blind system were made at the Technical University of Berlin, Germany. The test rooms were 3.5 m wide, 4.7 m deep, and 3.0 m high. The test room was equipped with a window system (made by Hüppe) consisting of a layer of prismatic panels for sun shading and semi-perforated blinds for redirecting diffuse daylight. Both layers were installed inside the window and covered the full height of the window. For clear sky measurements, the reference room was equipped with a standard, outdoor, grey, 80-mm-wide venetian blind set at a slat angle of +45° (view of ground when inside the room). For overcast sky measurements, the reference room had clear, unshaded glazing. For a detailed description of the test rooms, see Appendix 8.4.

Figure 4-5.7: Diagram of the Hüppe system



Because of its complex construction, the Hüppe system must be installed inside the room. The slat angle of the prisms is automatically adjusted according to the current sun position. The micro-controller unit that is responsible for the adjustment must be pre-programmed by the manufacturer for the specific location and room orientation in which the system is to be used.

Prismatic panel combined with blinds Berlin (52°N)	Interior Illuminance Level (% of lux)						Exterior Condition (klux)	
	Window zone		Intermediate zone		Rear wall zone			
	Test Room	Ref. room	Test Room	Ref. Room	Test Room	Ref. room	Evg	Evgs
Clear equinox: Noon	1,660	1,240	1,280	840	770	520	65	61
Clear equinox: 9:00	1,020	860	720	530	390	320	46	37
Clear equinox: 15:00	500	440	360	290	200	200	33	32
Clear summer: Noon	1,400	860	1,050	570	620	350	98	57
Clear summer: 9:00	820	670	600	420	320	250	75	33
Clear summer: 15:00	470	490	340	310	200	190	75	35

Note: The window and rear zone sensors were 0.6 and 4.2 m from the window, respectively. The intermediate zone is an average of data taken at 1.8 and 3 m from the window. "Sun" indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

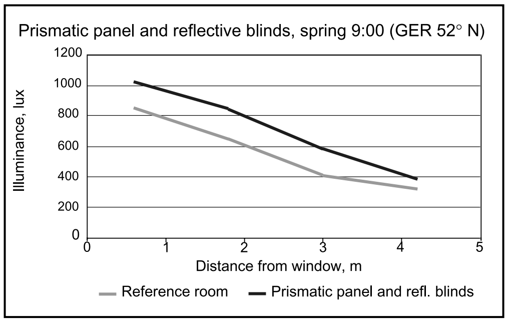
Overcast Sky

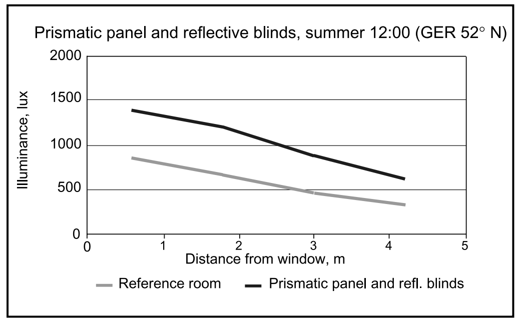
Under overcast sky conditions, the prismatic panel system was raised manually with the semi-perforated blind remaining. In this case, the illuminances were the same as in the reference room, which had no shading system. The window of the reference room is of equal size, clear, and nearly unobstructed.

Clear Sky

The results were compared with those for a reference room equipped with standard venetian blinds with a slat angle of 45°.

Under clear sky conditions, the Hüppe system increased the illuminance level in most cases. The system also works as a shading system, but due to the interior position of the prisms the shading factor was relatively low. The prisms and the slats allow only an extremely reduced view to the outdoors.





Conclusions (B)

For cloudy or overcast sky conditions without direct sunshine on the facade, the illuminance level was significantly reduced by the system. In this case, a sun sensor could be advantageous for automatically adjusting the slats or for lifting up and retracting the prisms to allow for an unobstructed window.

C. Prismatic Panel (Austria)

The following measurements of transmitted luminous flux were taken of three different types of prismatic panels at Bartenbach LichtLabor, Innsbruck, Austria.

In the polar diagrams below (Figure 4-5.8a), the percentage of transmitted daylight is given as a function of incidence angle, where the outgoing altitude (θ=0-90°) and azimuth (φ= -180° to 180°) angles are relative to the surface of the prismatic panel. The structured or serrated side of the panel is oriented to the exterior. In the interior light distribution diagrams (Figure 4-5.8b), the interior light distribution (percentage of the exterior luminance produced by a diffuse hemispherical light source) is given as a function of altitude and azimuth angles relative to the inside surface of a vertical window. A vertical section through the window falls along the -90°/+90° azimuthal axis, and the inward surface normal has an altitude of 90°. See Appendix 8.3 for a more detailed description of these types of measurements.

Light-Directing Panel (Siemens 48/5)

This panel is designed to redirect daylight deeper into a room and towards the ceiling. Normally, it is used in a vertical opening above eye level. In this case, the prismatic structure is oriented to the outside. The average diffuse transmittance of the panel is 48%. From

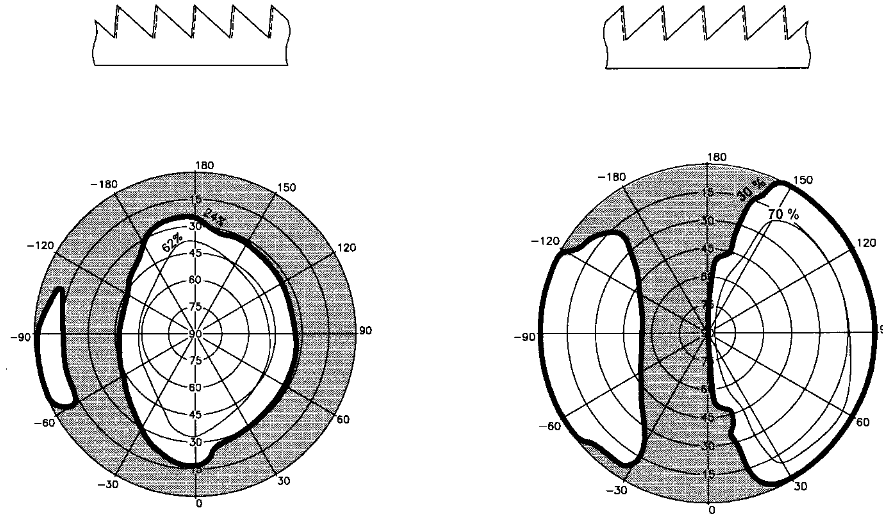


Figure 4-5.8: a) left: transmission of light as a function of incidence angle, where the structured side is oriented to the outside, ground is 90°, and zenith is -90°; b) right: inside light distribution based on a diffuse hemispherical light source on the structured side of the panel, ground 90°, zenith -90°

Figure 4-5.8a, it can be seen that the panel transmits light primarily at angles normal to the surface of the panel. The shaded area denotes values less than 24%. Figure 4-5.8b shows that most of the transmitted light is distributed into the right-hand side of the diagram, i.e., the upper part of the room, if the panel is oriented correctly. The shaded area denotes values less than 30% of the exterior luminance.

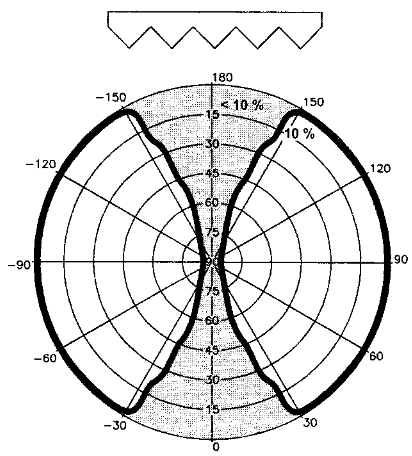


Figure 4-5.9: Angle-dependent transmission of the Siteco 45/45 sun-shading panel

Sun-Shading Panel (Siteco 45/45)

This panel is used as a movable sun-shading device. The average diffuse transmittance of the panel is 56%. In Figure 4-5.9, the shaded central portion of the diagram shows the outgoing angles where sun shading occurs. Therefore, the panel must be adjusted daily and seasonally so that sun can be blocked within this outgoing angular area.

Sun-Shading Panel (Siteco 62/28)

This panel is used as a fixed sun-shading system. The diffuse transmittance is 56% (panel only). A coated surface has been added to the prismatic structure (see Figure 4-5.10) so that the angle-dependent transmission diagram shows a larger angular area with low transmission. This means that the panel can remain in a fixed position. The shaded area denotes values less than 30%.

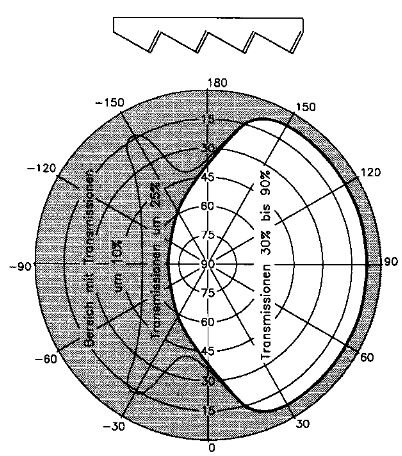


Figure 4-5.10: Angle-dependent transmission of the Siteco 62/28 sun-shading panel

D. Prismatic Film and Prismatic Panel (United Kingdom)

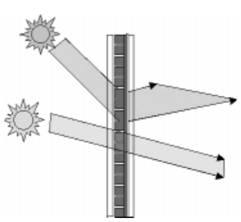
The Building Research Establishment (BRE) tested two separate systems in its mock-up office facility in Garston near London, United Kingdom (UK) [Aizelwood 1993]: a prismatic film system (prism angles 62° and 78°) and a Siemens prismatic light-directing panel (prism angles 45° and 90°).

In direct sun (summer and equinox), the prismatic film refracted sunlight and illuminated the ceiling in the centre of the room. Compared to clear glazing, the prismatic film raised illuminance levels in the middle and at the back of the room by about 10 to 20%. For low sun elevations (winter), the bright patch on the ceiling was nearer to the window, which reduced the illuminance level at the back by 30 to 40%. The film also performed less well under cloudy conditions (10 to 30% reduction), but provided glare control.

Under overcast conditions, the prismatic light-directing panel provides a uniform reduction in illuminance levels throughout the room of 35 to 40%. On clear summer days, the panel generally excluded sunlight, which reduced overall light levels in the room. On clear equinox days, illuminance levels were increased at the back of the room by more than 100%. However, this performance of the prismatic panel was rarely replicated during the study period. On clear winter days, as the sun got lower in the sky, light levels at the very back of the room were reduced by 50% because the sunlight that would have penetrated deep into the room was redirected onto the ceiling at the front. The prismatic panel provided good glare control in all conditions without the need for venetian blinds.

Laser-Cut Panel 4.6.

The laser-cut panel is a daylight-redirecting system produced by making laser cuts in a thin panel made of clear acrylic material.



4.6.1. Technical Description

Components

A laser-cut panel is a thin panel that has been divided by laser cutting into an array of rectangular elements. The surface of each laser cut becomes a small internal mirror that deflects light passing through the panel. The principal characteristics of a laser-cut panel are: (a) a very high proportion of light deflected through a large angle (>120°), (b) maintenance of

Figure 4-6.1: View through a laser-cut panel

view through the panel (see Figure 4-6.1), and (c) a flexible manufacturing method suitable for small or large quantities.

Light is deflected in each element of the panel by refraction, then by total internal reflection, and again by refraction (see Figure 4-6.2). Because all deflections are in the same direction, the deflection is highly efficient. The panels are usually fixed inside glazing units, but they may also be used as external glazing if the cut surface is protected by lamination between glass sheets. Normally the panels are cut at an angle perpendicular to the surface, but it is possible to make the cuts at a different angle for added control over the direction of the deflected light [Edmonds 1993, Reppel and Edmonds 1998].

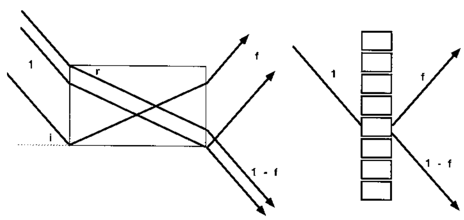


Figure 4-6.2: Showing the fraction "f" of light deflected in a prism and an array of prisms. The fraction f is given as a function of incidence angle in figure 4.6.5

Production

Panels are produced by laser cutting a sheet of clear acrylic (PMMA). They are designed to include a solid periphery and support sections. The laser cutter is programmed with the design.

Laser cuts are usually made right through the panels because this method requires less control of cutting speed and laser power than other approaches. For this reason, it is necessary to design the panel so that solid regions 10-20 mm wide are left to support the cut sections. For example, a panel 1000 mm x 600 mm that has laser cuts right through a 6 mm thick acrylic panel requires a 20-30-mm-wide solid periphery and two vertical solid support sections that are 10-20 mm wide. It is possible to cut only partway through the panel, e.g., 75% depth. However, a solid periphery is still necessary for structural strength.

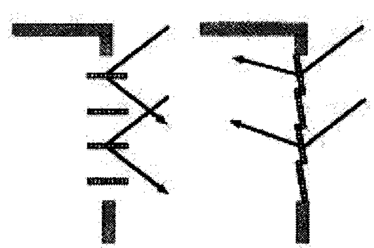


Figure 4-6.3: In louver or venetian form, laser-cut panels may be adjusted to the open, summer position to reject light or to the closed, winter position to admit light

Location in Window System

Laser-cut panels may be used in fixed and movable arrangements within a window system. There is view through the panels. However, even though laser-cut panels maintain high transparency with limited distortion of the view out, they should mainly be used for daylight apertures and not for view windows, or at least not when occupants are close to view windows. Because the panels redirect downward incoming light in an upward direction, it is desirable that they be installed above eye level in windows to avoid glare.

The panels may also be used in louver arrangements or, if produced in narrow widths, as venetian style arrangements. As movable louvers, the system rejects sunlight when the panels are in the open louver position (see Figure 4-6.3, above left) and redirects light when the panels are in the closed louver position (see Figure 4-6.3, above right). Whether in louver or venetian form, laser-cut panel panels may be adjusted to the open, summer position to reject light or to the closed, winter position to admit light.

Technical Barriers

The main technical barrier to laser-cut panels is their cost, approximately 100 euros per square metre. At present, the panels are designed and cut to suit the size and shape of specific windows. They can also be produced in a laminated sheet that can be cut to size, but this process has not yet been established commercially.

4.6.2. Application

Laser-cut light-deflecting panels can be applied as:

- a fixed sun-shading system for windows, as shown in Figure 4-6.4,
- a light-redirecting system (fixed or movable), as shown in Figure 4-6.8, or
- a sun-shading/light-directing system for windows (in louvered or venetian form) as shown in principle in Figure 4-6.3.

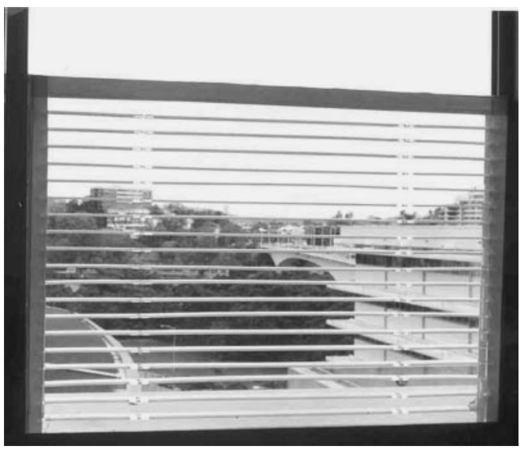


Figure 4-6.4: Laser-cut panels that are 20 mm wide panels can be installed venetian style between two glass panes to form a double-glazed window. This angle-selective form of window rejects a high proportion of incident sunlight while maintaining good viewing characteristics. (See Figure 4-6.7 for irradiance versus time of day for an east-facing window at the latitude of Paris, 48.8°N.)

4.6.3. Physical Principles and Characteristics

Fixed Light-Directing System

A laser-cut panel with a cut spacing to cut depth ratio (D/W) of 0.7 that is fixed vertically in a window will deflect nearly all light incident from above 45° and transmit most light incident from below 20° (see Figure 4-6.5). Thus, a high fraction of light is deflected by the panel onto the ceiling which then acts as a secondary source of diffuse reflected light in a similar way to a light shelf.

Light-Directing System in Windows

A vertical laser-cut panel strongly deflects light incident from higher elevations, >30°, while transmitting light at near normal incidence with little disturbance, thus maintaining view. Figure 4-6.5 shows the fraction of light deflected versus elevation angle of incident light on a vertical laser-cut panel. The panel has very low glare because the deflected light is directed strongly upwards while the undeflected light continues in the same downward direction as the incident light. The scattered light is low because no rounded surfaces are produced in the manufacturing process. Nevertheless, it is desirable to use laser-cut panels in the upper half of windows.

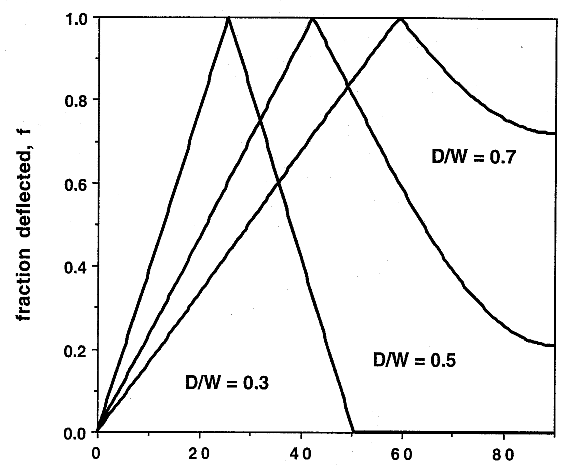


Figure 4-6.5: The fraction of light deflected versus elevation of incident light for a vertical laser-cut panel with three different cut spacing (D) to cut depth (W) ratios

Sun-Shading System in Windows

If an array of narrow panels is mounted horizontally in a window, i.e., with the face of the panels horizontal, then sunlight from higher elevations is deflected back to the outside. Thus, this system is very effective for excluding sunlight while being entirely open for viewing (See Figures 4-6.6 and 4-6.7).

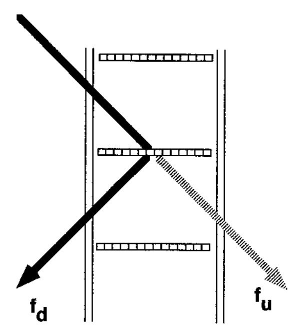


Figure 4-6.6: Horizontal laser-cut panels form an angle-selective window that deflects light to the outside

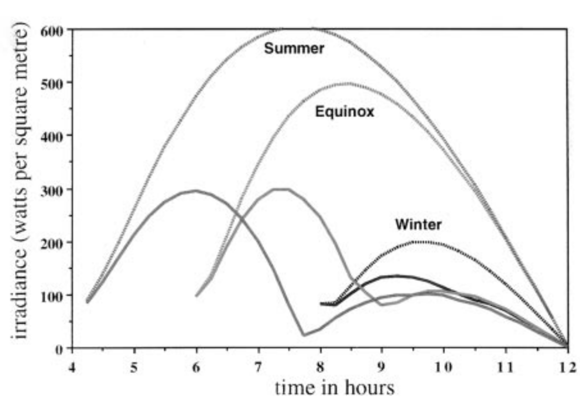


Figure 4-6.7: The irradiance through an east-facing angle- selective window at the latitude of Paris (48.8°N)

4.6.4. Control

Laser-cut panels are usually fixed as a second internal glazing in windows or skylights. However, when laser-cut panels are installed as an internal glazing in awning windows, then, as the awning windows are tilted open to the outside, high-elevation light is deflected more deeply into the room. In principle, the tilt of the panel can be continuously adjusted to obtain optimum penetration of sunlight. (Figure 4-6.8 illustrates the deflection of sunlight over the ceiling of a room by laser-cut panels in awning windows.)

4.6.5. Maintenance

If the panels are fixed inside of existing glazing or skylights, no maintenance is required. When panels are laminated between thin sheets of glass and installed as single glazing, the maintenance is the same as for glass.

4.6.6. Cost and Energy Savings

The cost of the panels is approximately 130 euros per square metre for small areas of panel (< 20 m^2). For larger areas, the cost approaches 100 euros per square metre.

Energy savings depend on the application. For example, laser-cut panels fixed in the upper half of a window to deflect light deeply into a room may increase the natural light by 10% to 30% depending on sky conditions. If the panels can be tilted out from the window, both light collection and penetration into the building can be dramatically increased.

4.6.7. Some Examples of Use

Figure 4-6.8: Laser-cut panels in awning windows deflecting sunlight over the ceiling of a classroom (Kenmore South State School, Brisbane, Australia)

4.6.8. Simulations and Measured Results

Test room measurements were conducted for laser-cut panels at two test sites. Norway conducted tests on a vertical panel. Germany conducted tests on an exterior, 20° tilted panel.

Algorithms have been developed to incorporate laser-cut panels into the lighting simulation programme ADELINE and Radiance.

A. Vertical Laser-Cut Panel (Norway)

The Norwegian University of Science and Technology (NTNU) tested a vertical laser-cut panel in an occupied office building at Sandvika, Norway (near Oslo) at latitude 59ºN. In the test room, the laser-cut panel was installed in the upper part of the window (Figure 4-6.9). The reference room had clear, unshaded glazing of equal size to the test room. See detailed test room description in Appendix 8.4.

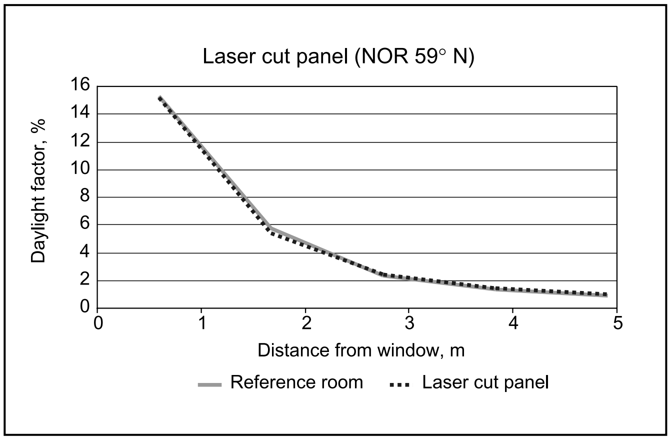
Figure 4-6.9: View to the outside from the test room with laser-cut panels installed in the upper, horizontal window (sunny day). A centre line aluminium section is used to locate measurement points

Laser-cut panel Norway: 59°N Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	5.4%	5.8%	2.5%	2.3%	1.0%	0.9%	12.2	5.5
Clear winter: Noon	Sun	Sun	Sun	Sun	2,230	1,240	23.4	78.8
Clear winter: 15:00	1,400	1,150	680	480	320	190	5.2	23.4
Clear equinox: Noon	7,620	4,730	4,200	2,540	1,710	1,220	58.5	96.6
Clear equinox: 15:00	2,720	2,630	1,370	1,120	720	460	38.7	62.7
Clear summer: Noon	4,790	3,700	2,660	1,800	970	700	85.7	77.1
Clear summer: 15:00	1,470	1,360	790	630	390	260	63.9	48.4

Note: The window, intermediate, and rear zone sensors were 1.67, 2.75, and 4.91 m from the window, respectively. "Sun" indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

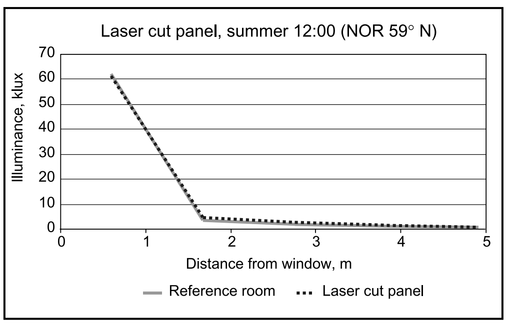
Overcast Sky

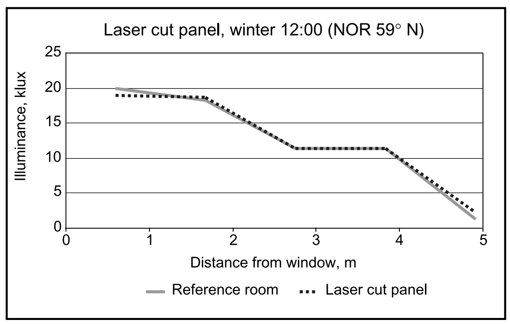
The test room and the reference room windows are identical except for the upper glazing area where a laser-cut panel is installed in the test room. As can be seen from the graph below, the laser-cut panel makes almost no change in the lighting level or distribution in the room.



Clear Sky

Under clear skies, the laser-cut panel increases the lighting level in all seasons of the year and throughout most of the day, especially in the intermediate zone of the room.





Conclusion (A)

The reduction of the light penetration through the laser-cut panel compared to an unobstructed window is smaller than what is normally experienced with blind systems. Even in the fixed position, the laser-cut panel improves the light distribution somewhat through most of the day and year.

B. Exterior, Tilted Laser-Cut Panel (Germany)

An exterior laser-cut panel covering the upper one-third (60 cm) of a glazing area was tested at Technical University of Berlin (TUB) in unfurnished mock-up offices in Berlin (latitude 52°N, longitude 13°E). The panel was tilted 20° to achieve a best compromise between light penetration and glare in summer.

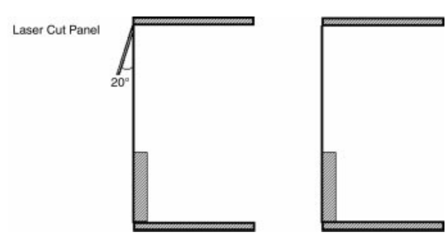


Figure 4-6.10: Section of facade of the test room (left) and reference room (right)

Production

Panels are produced by laser cutting a sheet of clear acrylic (PMMA). They are designed to include a solid periphery and support sections. The laser cutter is programmed with the design.

Laser cuts are usually made right through the panels because this method requires less control of cutting speed and laser power than other approaches. For this reason, it is necessary to design the panel so that solid regions 10-20 mm wide are left to support the cut sections. For example, a panel 1000 mm x 600 mm that has laser cuts right through a 6 mm thick acrylic panel requires a 20-30-mm-wide solid periphery and two vertical solid support sections that are 10-20 mm wide. It is possible to cut only partway through the panel, e.g., 75% depth. However, a solid periphery is still necessary for structural strength.

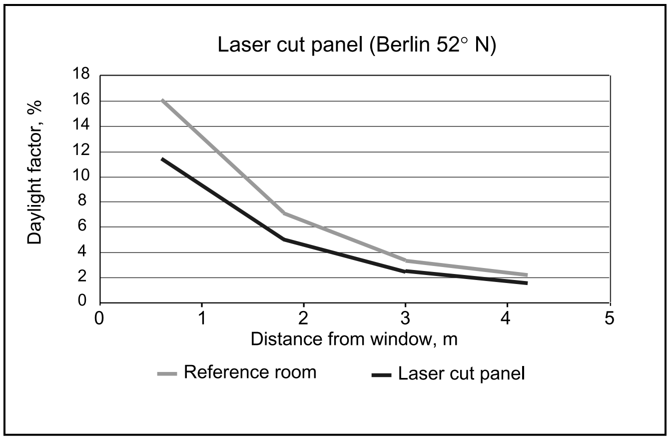
Laser-cut panel (20° tilt) Berlin: 52.47°N, 13.4°E Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	11.0	14.9	3.8	4.9	1.7	2.1	25	9
Overcast (DF%)	11.5	16.1	3.8	5.3	1.6	2.2	39	12
Clear equinox: Noon	2,650	1,460	Sun	1,000	1,320	570	74	77
Clear equinox: 9:00	1,900	1,010	1,180	600	630	340	51	46
Clear equinox: 15:00	1,100	480	670	300	360	190	48	46
Clear summer: Noon	2,730	830	1,600	550	920	330	97	58
Clear summer: 9:00	1,660	630	910	390	450	230	75	34
Clear summer: 15:00	1,220	500	720	320	390	200	75	36

Note: The window and rear zone sensors were 0.6 and 4.2 m from the window, respectively. The intermediate zone is an average of data taken at 1.8 and 3 m from the window. "Sun" indicates sunlight striking the sensors. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing south. DF% is the daylight factor.

FIGURE 4-6.11: Interior view of the TUB test room with the tilted laser-cut panel in the upper third of the glazing. The lower part of the glazing has no other system (overcast sky case)

Location in Window System

Laser-cut panels may be used in fixed and movable arrangements within a window system.

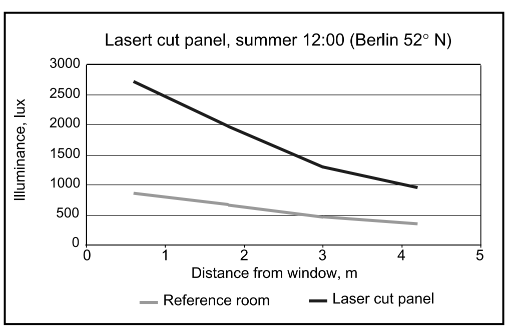


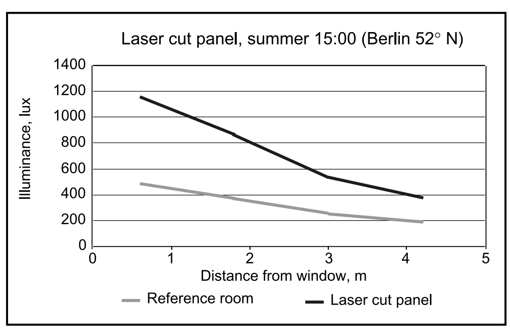
Clear Sky

Under clear skies, the lower two-thirds of the test room window and all of the reference room window were covered with exterior venetian blinds with slightly curved slats, downward tilted at a +45° slat angle. The slats were 80 mm in width, with a grey, diffusely reflecting surface. The position of the blinds caused a partly obstructed directional view to the outside.

Figure 4-6.12: The TUB test room with the tilted laser-cut panel in the upper third of the glazing. The lower part of the glazing has an exterior blind to protect against direct sun (clear sky case)

Under clear skies, the illuminance level is distinctly increased compared with that in a reference room equipped with standard exterior venetian blinds. Direct sun is admitted for some sun positions (e.g., equinox at noon). To avoid this, the tilt angle of the laser-cut panel will have to be adjusted seasonally.





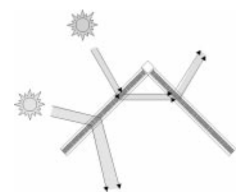
Conclusions (B)

Under overcast sky conditions, the laser-cut panels do not change daylighting level or light distribution dramatically compared to clear glazing.

Under clear sky conditions, daylighting performance can be significantly improved if the position of the panels is adjusted depending on time of day and year (relative to sun position). Adjustment of the tilt angle also improves the system's ability to redirect light and to work as a shading device. Because the system is not suited for view windows, supplementary protection against direct sun and glare is necessary. No colour dispersion has been observed.

4.7. Angular Selective Skylight (Laser-Cut Panel)

The angular selective skylight (Figure 4-7.1) incorporates a pyramid or triangle configuration of laser-cut panels within the transparent skylight cover to provide angular selective transmission.



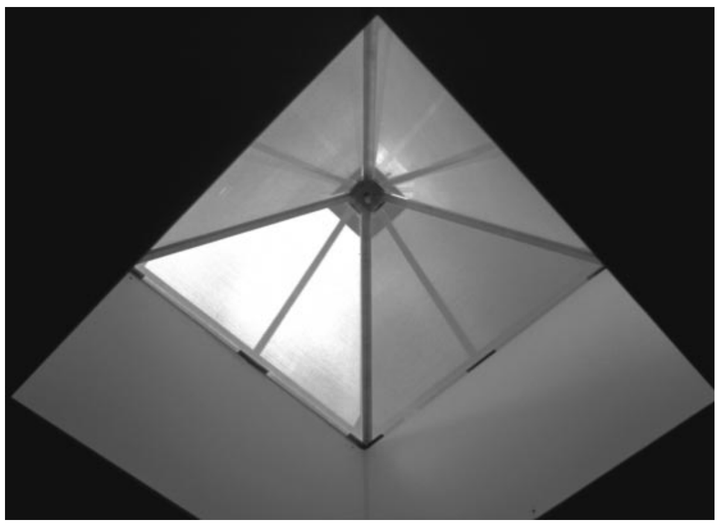


FIGURE 4-7.1: THE SKYLIGHTS USED AT THE WATERFORD SCHOOL IN BRISBANE, AUSTRALIA, USE LASER-CUT ACRYLIC PANELS TO ACHIEVE ANGULAR SELECTIVE TRANSMITTANCE. LIGHT FROM HIGH SUN ANGLES IS REFLECTED WHILE DIFFUSE, LOW-ANGLE SKYLIGHT AND SUNLIGHT PENETRATE THE SKYLIGHTS

4.7.1. Technical Description

Components

An angular selective skylight is a conventional clear pyramid or triangular type skylight. Laser-cut light-deflecting panels are incorporated inside the clear outer cover forming a double glazing (Figure 4-7.2). This system transmits more low-elevation light and less high-elevation light. Normally, a diffusing panel is used at the ceiling aperture.

Production

Laser-cut panels are produced by making fine cuts through a thin panel of acrylic (PMMA) [Edmonds et al. 1996]. Four panels, each cut to a triangular shape, are fixed inside a pyramid-type skylight. For a triangular or gable-type skylight, the panels are cut to rectangular form and fixed to the interior of the skylight frame. Usually the panels are cut from 6-mm-thick acrylic, and the cuts are spaced 4 mm apart. Useful tilt angles for the panels in the skylight range between 45° and 55° for the tropics and subtropics where rejection of high-elevation sunlight is critical. For high latitudes where admittance of low-elevation light is more important, tilt angles between 25° and 35° are used.

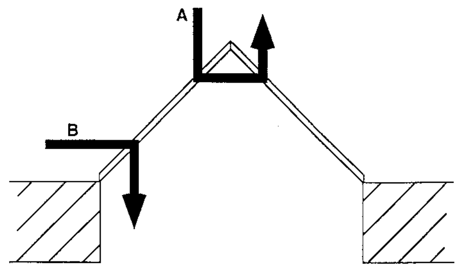


Figure 4-7.2: High-elevation light, A, is rejected and low-elevation light, B, is deflected to the interior

Angular selective skylights are manufactured and sold under licence in Australia by Skydome Ltd., Sydney, in sizes ranging from 0.8 m^2 to 2.4 m^2.

Location in Window System

Skylights are installed in the roof of a building. The primary function of an angular selective skylight is to provide relatively constant irradiance to the interior during the day and to reduce the tendency to overheat the building on summer days.

Technical Barriers

Because angular selective skylights reject high-elevation light, they are not suitable in climates with predominantly overcast skies. They were designed specifically for low-latitude climates with clear skies. However, the design may be applied in high-latitude, clear sky climates such as Canada to boost the irradiance from low-elevation winter sunlight. These skylights are not suited to high-angle roofs because a curb must be used to keep the aperture horizontal, and this adds to their cost.

4.7.2. Application

Angular selective skylights are especially suited for natural lighting of ventilated or air-conditioned buildings with extensive floor area and low-angle roofs, such as supermarkets and schools (see Figure 4-7.5).

Low Latitudes

At low latitudes in subtropical climates, it is important to reject high-elevation sunlight to avoid overheating at midday. Thus the tilt angle of the skylight panels is greater than 45°, as in Figure 4-7.2. As illustrated in Figure 4-7.3 for a triangular skylight (panel tilt angle = 55°), the transmission of skylight falls rapidly as the elevation of incident sunlight approaches 90°, demonstrating that this type of skylight enhances low-elevation input and rejects high-elevation input.

High Latitudes

At high latitudes, it is important to enhance the input of low-elevation sunlight and to maintain the input of high-elevation diffuse skylight. Thus, for high latitudes, the tilt angle of the laser-cut panels is 35° or less. As illustrated in Figure 4-7.3 for a triangular skylight (panel tilt angle 30°), the enhancement of low-elevation light input is considerable, and the input of high-elevation light is only slightly decreased.

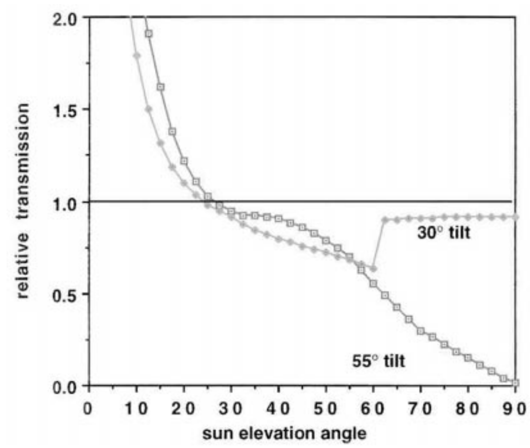


Figure 4-7.3: Transmission of an angular selective skylight relative to an open skylight for tilt angles of 30° and 55°

Skylights

Skylights in buildings with low ceilings usually provide too much light directly below the skylight and too little to the sides of the skylight. If laser-cut panels are used in an inverted V or inverted pyramid structure below a skylight, downcoming light may be deflected over the ceiling, improving the distribution of light to the interior (see Figure 4-7.6 for an example of a light-spreading skylight installed in a very large room).

4.7.3. Physical Principles and Characteristics

Conventional skylights strongly transmit high-elevation light and weakly transmit low-elevation light. The pyramid or triangle configuration of laser-cut panels in angular selective skylights (Figure 4-7.1) deflects low-elevation light down into the skylight and increases transmittance of this light to the building interior. When the tilt angle of the laser-cut panels is greater than 45°, they reduce transmittance of high-elevation light by deflecting it from one panel across to the opposing panel and back out of the skylight (Figure 4-7.2). The detailed performance of angular selective skylights depends on the spacing of the laser cuts in the panel, the tilt angle of the pyramid or triangle configuration of the panels, the well depth of the skylight, the time of day and season, and the sky conditions. As the skylight well depth increases, its performance at low-elevation light angles increases rapidly. The most useful measure of performance is to compare the irradiance through an angular selective skylight with the irradiance through an open skylight as a function of the time of day (Figure 4-7.4 for a skylight with zero well depth).

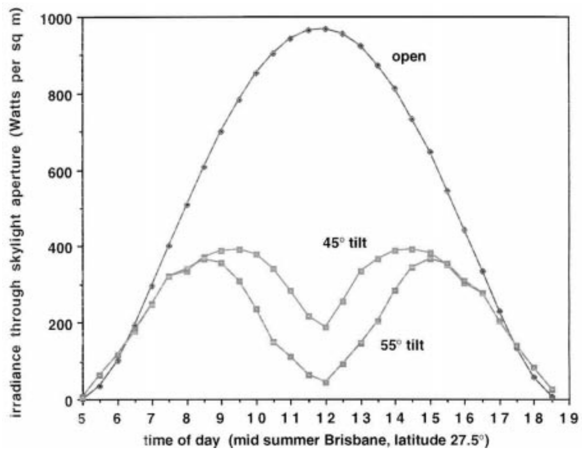


Figure 4-7.4: Irradiance versus time of day through the aperture of open and angular selective skylights with tilt angle 45° and 55° in mid summer at latitude 27.5°

4.7.4. Control

Angular selective skylights are always used as fixed systems; their angle-dependent transmittance provides time-dependent control of irradiance to the building's interior.

4.7.5. Maintenance

No maintenance is required beyond normal skylight maintenance.

4.7.6. Cost and Energy Savings

An angular selective skylight is essentially a conventional skylight with a double glazing of laser-cut panels added. The extra cost may be calculated based on 100 euros per square metre for laser cut panel. Typically, the installed cost of a 0.8 m^2 conventional pyramid skylight is about 500 euros whereas the installed cost of a 0.8 m^2 angular selective pyramid skylight is 600 euros.

Energy savings can be significant since angular selective skylights can reduce overheating. Electrical lighting use can also be reduced compared to buildings with no skylights or buildings that use smaller skylights to control overheating.

4.7.7. Some Examples of Use

- Waterford State School, Brisbane, Australia (Figure 4-7.5)
- Konica Office Building, Sydney, Australia
- Canugra Parish Church, Queensland, Australia
- Mount Cootha Herbarium, Brisbane, Australia (Figure 4-7.6)

Figure 4-7.5: Angular selective skylights in a classroom at Waterford State School, Brisbane, Australia

Figure 4-7.6: Laser-cut panels installed in “V” form below a skylight aperture. Downcoming light from the skylight is deflected over the ceiling, distributing light more evenly within the room (Mount Cootha Herbarium, Brisbane)

4.7.8. Simulations and Measured Results

An installation of angular selective skylights at Waterford School was selected to test the technology because two identical-size school buildings, each 14 m x 9 m, were available. One was used as the trial building with eight 0.8-m^2 skylights (Figure 4-7.5) and the other with no skylights as the reference building. Both buildings had strong external shading, including absorbing glass, on the windows.

These measurements did not follow the monitoring protocol. Measured illuminances at desk-top level along the central axis of each building are shown in Figures 4-7.7 and 4-7.8. Figure 4-7.7 compares illuminance levels in the trial and reference building under overcast skies at about 15:00 (horizontal ambient illuminance about 20 klux). Figure 4-7.8 compares illuminance under extremely bright summer conditions near noon (direct plus bright cloud-reflected light, horizontal ambient illuminance about 140 klux). While the external illuminance varies by about seven times, the internal illuminance varies by only three times. Simulations were also performed [Edmonds et al. 1996].

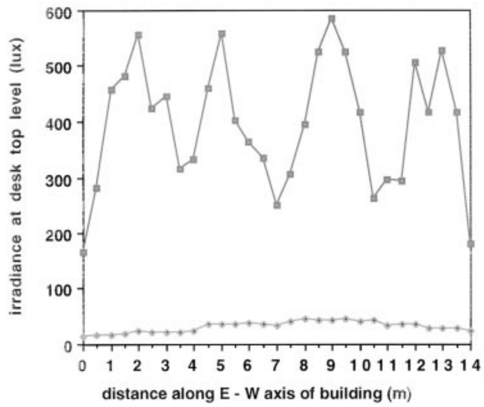


Figure 4-7.7: Illuminance at desk-top level in the trial building (upper curve) and in the reference building (lower curve) for overcast conditions

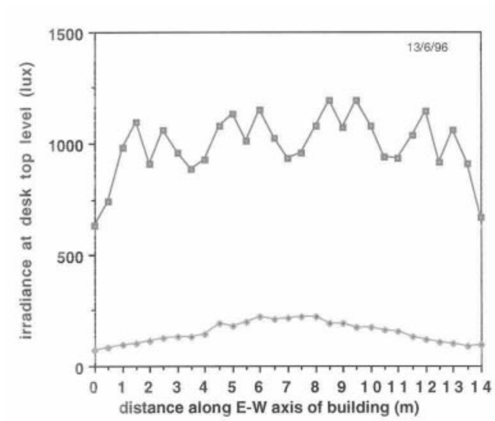
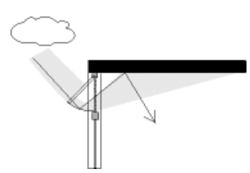


Figure 4-7.8: Illuminance level at desk-top level in the trial building (upper curve) and in the reference building (lower curve) for very bright conditions

Light-Guiding Shades 4.8.

A light-guiding shade is an external shading system that redirects sunlight and skylight onto the ceiling.



4.8.1. Technical Description

Components

A light-guiding shade consists of a diffusing glass aperture and two reflectors designed to direct the diffuse light from the aperture into a building at angles within a specified angular range (Figure 4-8.2). Usually the angular range of light distribution in the building is designed to extend from horizontal up to an elevation of about 60°. The lower elevation is set at zero or horizontal to avoid glare. The light-guiding shade is fixed in the same way as an external shade over a window; it shades the window from direct sunlight as a normal shade does.

Figure 4-8.1. Light-guiding shades mounted on the north windows of the Mount Cootha Herbarium, Brisbane, Australia

Production

Light-guiding shades are more complicated and more precisely defined than conventional shades. Highly reflective material, such as bright-finish aluminium, must be used for its inner surfaces. However, the method of light-metal fabrication is essentially the same for both types of shades.

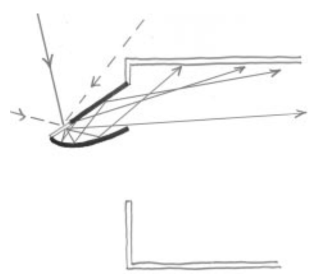


Figure 4-8.2. Principle of the light-guiding shade

Location in Window System

Light-guiding shades are installed over the upper one-third or one-half of a window system. The shades have vertical side panels for support and additional shading.

Technical Barriers

The principal barrier to light-guiding shades is that they cost more than conventional shades, primarily because of the cost of the high-reflectance metal sheet from which the light guiding shade is manufactured and the requirement that the reflective material be formed accurately to limit the spread of output light. One problem observed in practise is that light-guiding shades tend to leak water. This problem can usually be corrected with small drain holes.

4.8.2. Application

In the subtropics, windows are almost always shaded by wide eaves, external and internal shades, and reflecting or absorbing glass. Consequently, the daylight entering a window is much reduced. Daylight levels in shaded subtropical buildings are well below levels in buildings with unshaded windows in more temperate climates. It is possible to adapt the form of an external shade so that it guides into the building some of the light that falls onto the shade. If this adaptation is made carefully so as to avoid glare and to direct light deep into a room, it is possible to enhance the room's daylighting while shading direct sunlight. This is a light-guiding shade's objective (Figure 4-8.1).

Light-guiding shades may be used in any building that uses external shading of windows. All daylight that enters through the light-guiding shade is directed over the ceiling; therefore the shade is a source of diffuse light, which is non-luminous when viewed by occupants of the room and is therefore entirely free of glare. Figure 4-8.3 compares the illuminance of rooms with a conventional shade and with a light-guiding shade of the same size. It is evident that daylighting is greatly improved and that the daylight source is free of glare when a light-guiding shade is used. The ceiling from which the light is reflected may become a source of glare if gloss paint is used, however. Usually a ceiling painted in flat white prevents glare problems.

Figure 4-8.3: compares the daylight in a trial room with a conventional shade (left) and a light-guiding shade (right). The outer edge of the shade is the horizontal yellow band visible through the lower window. Note the low luminance of the output aperture of the light-guiding shade which is directing light only to the ceiling (right photo, upper aperture)

4.8.3. Physical Principles and Characteristics

Light-guiding shades are designed to improve the daylighting of rooms in subtropical buildings that have external shading to reduce radiant heat gain through windows. Therefore, their daylighting performance should be measured relative to a shaded window, not an open window.

The input light to the light-guiding shade comes from a wide range of directions. However, because the input aperture is diffusing, the directional dependence of the input light is removed. Because the light entering the input aperture is diffuse, it is possible to use the principles of non-imaging optics to design the light-guiding reflectors so that the output light falls within an exactly defined angular range. This range can be as narrow or as wide as desired. However, a very narrow output angular range requires a long reflective light guide and a small input-aperture-to-output-aperture ratio. Thus, for a narrow output range, the system is able to collect only a small fraction of the light incident on the shade; as a result, the potential for improved daylighting is small. A compromise must be made between the precision with which light is directed into the room and the amount of light being directed. Because light-guiding shade systems are designed to boost the daylight from the very low level in strongly shaded rooms, it is desirable to direct the light into a relatively wide-output angular range, e.g., 0° to 60°, and to use a larger input-aperture-to-output-aperture ratio—usually in the ratio of 1:2 to maximise total daylight input. Much of the daylight falls on the ceiling close to the window, but because light levels close to the window are often very low, the light-guiding shade can improve interior lighting levels.

If the shade's reflective surfaces are accurately manufactured, then the output beam is very well-defined. If the system is designed so that no light is emitted below the horizontal, then the light-guiding shade source appears dark when viewed from inside the building (Figure 4-8.3). Although this is ideal for reducing glare, occupants who are not familiar with the system may think it is not working. Therefore, there may be a good reason to direct a small amount of light downward, e.g., an angular range from -5° up to +50°. The design equations are outlined in the patent [Edmonds 1992].

4.8.4. Control

Light-guiding shades are fixed in position. Control of the light direction is achieved by the optics.

4.8.5. Maintenance

There is no maintenance other than occasional cleaning of the external input aperture glazing.

4.8.6. Cost and Energy Savings

The cost of a light-guiding shade should be compared with the cost of a conventional external shade or equivalent shading system. Manufacturing costs are much higher than the costs for conventional shades because of the precisely shaped, high-reflectance surfaces required. However, installation and maintenance costs are the same, and the daylighting performance is much superior to that of conventional shades (Figure 4-8.3).

There is a considerable energy benefit from light-guiding shades. Conventional external shades significantly reduce daylight input and are designed to exclude all direct sunlight. Typically, the average daylight level in a room with a strongly shaded window is less than 50 lux. Under clear sky conditions, a light-guiding shade can produce a work plane illuminance of more than 1000 lux at a 5-m room depth. Under overcast sky conditions, the average illuminance obtained would be about five times smaller, i.e., 250 lux. Thus, a light-guiding shade can boost daylight levels in a 5-m-deep room to regulation levels. This example illustrates the gains possible with a light-guiding shade system. In practise, gains will depend on the shape and size of the window; the slope and reflectance of the ceiling, walls, and floor; the type of glazing on the window; and the ambient conditions.

Figure 4-8.4: Light-guiding shade on a building at Regents Park State School, Brisbane, Australia

4.8.7. Some Examples of Use

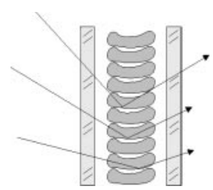
- Regents Park State School, Regents Park, Queensland, Australia (Figure 4.8.4)
- Mount Cootha Herbarium, Brisbane, Australia

4.8.8. Simulations and Measured Results

Test room studies were conducted at Brisbane, Australia, but these measurements did not follow the monitoring protocol.

Sun-Directing Glass 4.9.

Concave acrylic elements stacked vertically within a double-glazed unit redirect direct sunlight from all angles of incidence onto the ceiling.



4.9.1. Technical Description

Components

The main component of a sun-directing glass system is a double-glazed sealed unit that holds the acrylic elements. This sealed unit is normally placed above the view window. The unit's solar heat gain coefficient is 0.36, and its U-value is about 1.3 W/m^2K (depending on the combination of glass and gas fill). A sinusoidal pattern on the interior surface of the window unit can be used to spread outgoing light within a narrow horizontal, azimuthal angle. A holographic film on the exterior glass pane can also be used to focus incoming daylight within a narrow horizontal angle [Kischkoweit-Lopin 1996].

An important part of the system is the ceiling, which receives the redirected light and reflects it down to the task areas. Tilted reflective elements in the ceiling can be used to concentrate reflected light to specific task areas. A simple matte white ceiling also works well to redirect light; the resulting illumination will be more diffuse.

Production

Light-guiding acrylic elements are produced by extrusion. The elements are stacked and placed in an ordinary, sealed, double-glazed unit. When holograms are used for horizontal deflection of daylight, they are produced using a holographic film that is exposed to an interference pattern of two or more laser beams. The film is then placed between two sheets of glass which form the outer pane of the sealed unit. The sinusoidal surface can be produced online during the extrusion process by a CO_2-laser beam or afterwards by laser, mechanically.

Figure 4-9.1: Sun-directing glass attached above the normal viewing window in the ADO office building, Cologne, Germany

Location in Window System

Sun-directing glass is placed in the window area above eye height in order to avoid glare and other visibility effects. It can also be placed in front of the facade, or behind it in retrofit situations. The height of the area with sun-directing glass should in most cases be about 10% of the height of the room. The normal lower viewing window can be shaded by conventional blinds.

Sun-directing glass can also be placed in rooflights to aid penetration of sunlight in atria or halls. The glass should be sloped at an angle of about 20° to redirect sunlight from lower sun positions (Figure 4-9.3).

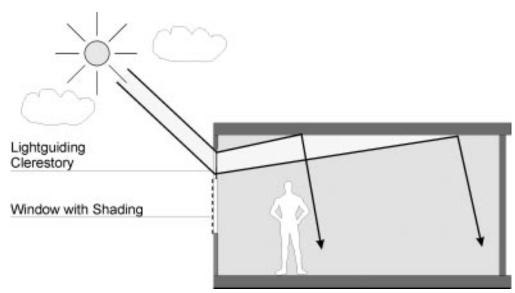


Figure 4-9.2: Sun-directing glass in the clerestory portion of the window

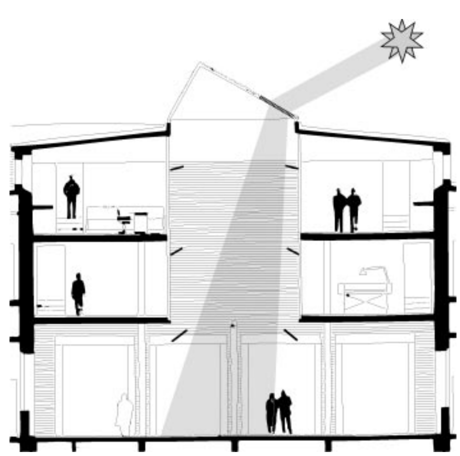


Figure 4-9.3: Sun-directing glass used in a rooflight to daylight an atrium

Technical Barriers

Sun-directing glass is commercially available. The only real barrier to its use is cost. Sun-directing glass also looks different from a normal window; it may appear to be somewhat "milky", which may interrupt the design of the facade, especially if most of the facade is transparent glass.

4.9.2. Application

The system is designed for use in direct sunlight. The best orientation on a facade is south in moderate climate zones (in the northern hemisphere). On west or east facades, it is only useful in the morning or afternoon. The system also deflects diffuse light, but the illuminance level achieved is much lower than with direct sunlight. Thus, for north facades, the elements have to be larger.

The profile of the acrylic elements has been designed for specific latitudes. The optimum sun altitude for the sun-directing glass is between 10–65° (Figure 4-9.4). In tropical regions where sun altitudes are higher, the sun-directing glass should be installed at a tilted vertical angle so as to redirect more light. In this case, the geometry of the sun-directing elements will have to be changed to prevent glare. A light-directing rooflight should be installed with a slope of about 20° towards the sun.

4.9.3. Physical Principles and Characteristics

Sun-directing glass deflects light in the horizontal plane as well as the vertical. Thus, light can reach the depth of a room for all solar positions without the need for movable parts in the building facade. Vertical deflection is achieved by the shape of the acrylic elements. Horizontal deflection is achieved either by holographic optical elements or by a sinusoidal glazing surface.

Vertical Deflection

Incoming light is focused by the first surface of the acrylic elements (Figure 4-9.4) and redirected by total reflection at the lower surface of the profile. It is spread slightly towards the ceiling when it leaves the elements.

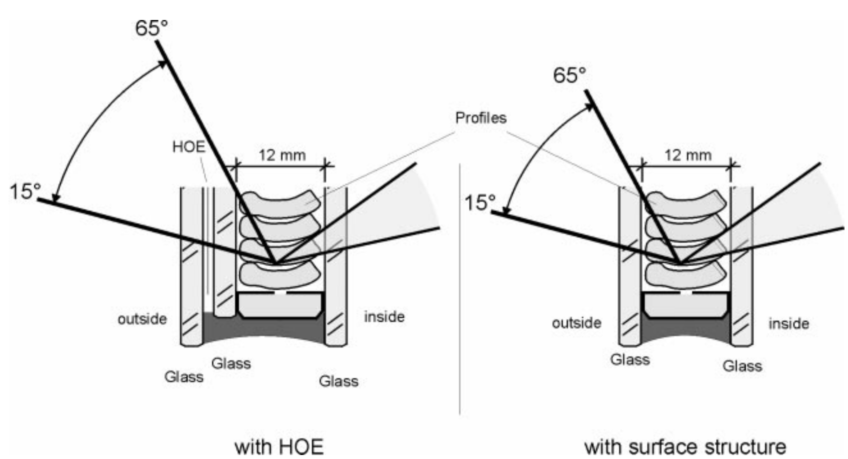


Figure 4-9.4:

Vertical section

Horizontal Deflection

To spread the light more broadly across the width of the room, holographic optical elements or a certain sinusoidal surface structure at the interior glass pane can be used to deflect light horizontally within the room.

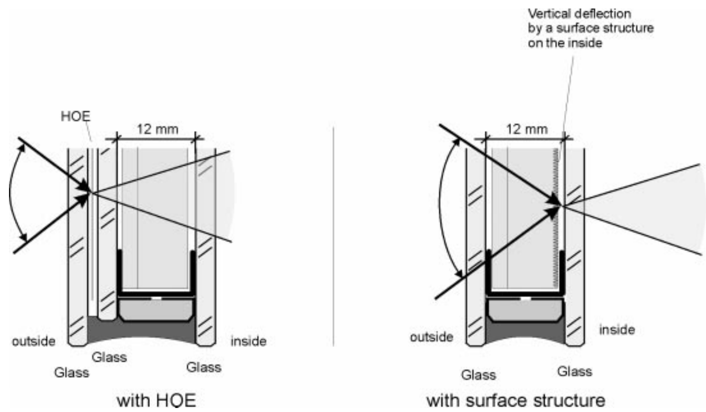


FIGURE 4-9.5: HORIZONTAL SECTION (PLAN VIEW)

4.9.4. Control

Sun-directing glass does not include any movable or adjustable parts, so there is no need for control.

4.9.5. Maintenance

As the sun-directing profiles are installed between two glass panes, no maintenance is necessary other than cleaning the glass.

4.9.6. Cost and Energy Savings

The price difference between sun-directing glass and standard insulated double glazing is about 200 euros per square metre for the sun-directing element itself (about 12 euros per square metre floor area). This price is expected to decrease for large-scale production. Sun protection is not necessary in front of the sun-directing glass, so these costs can be reduced.

4.9.7. Some Examples of Use

- Geyssel office building, Cologne, Germany (see Section 4-9.8)
- Office building ADO, Cologne, Germany

The ADO office building was refurbished with sun-directing glass. The glass was installed in some places by replacing the existing window glazing and in other places by mounting the units in front of the existing windows (Figure 4-9.1). The ceiling was white and diffusely reflecting. The electric lighting was controlled by a photosensor on the roof (open-loop control strategy). See the *IEA SHC Task 21 Daylight in Buildings: 15 Case Studies from Around the World.*

4.9.8. Simulations and Measured Results

Measurements were made of the sun-directing glass in vertical windows. The measurements were not made according to the monitoring protocol.

A. Sun-Directing Glass with Reflective Interior Ceiling (Germany)

Sun-directing glass was applied in the new Geyssel office building in Cologne within a ground floor office room approximately 9 m long and 7 m deep. The ceiling height was 3 m. There was a reflecting ceiling with aluminium lamellas tilted towards the window to distribute the light onto the work plane with minimum loss. The electric lighting supplemented the daylight to achieve an illuminance of 500 lux. The electricity demand for electric lighting was monitored continuously for a year. Significant lighting energy savings from sun-directing glass were measured, but the reference room without the daylighting system was in this case without automatic lighting controls (see IEA SHC Task 21 *Daylight in Buildings: 15 Case Studies from Around the World* and *Survey of Architectural Solutions* on this book's CD-ROM).

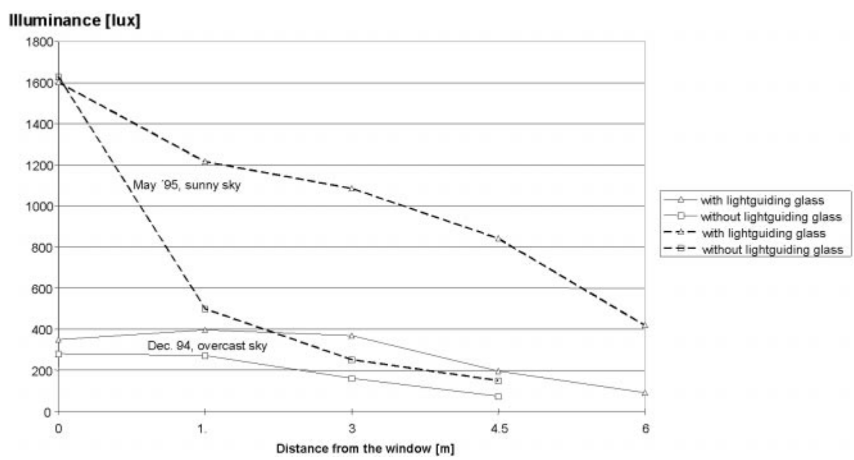


Figure 4-9.6: Measured interior illuminance on December 9, 1994 (overcast) and on May 3, 1995 at 14:30. The lower window shades were closed

B. Sun-Directing Glass (Germany)

The Institute for Light and Building Technique (ILB) at the University of Applied Science in Cologne, Germany, tested sun-directing glass mounted at a height of 2.05 m in the test room. The sun-directing elements themselves were 40 cm high and were installed behind the existing window. In front of the lower viewing section of the window of the test room, a black venetian blind was installed. In the reference room, black venetian blinds completely covered the window. During clear sky measurements, the slats in both rooms were tilted at the same angle to block direct sun: 40° in the summer, 80° in winter, and 60° during the equinox. During overcast sky measurements, the slat angle was horizontal (0°) in both rooms.

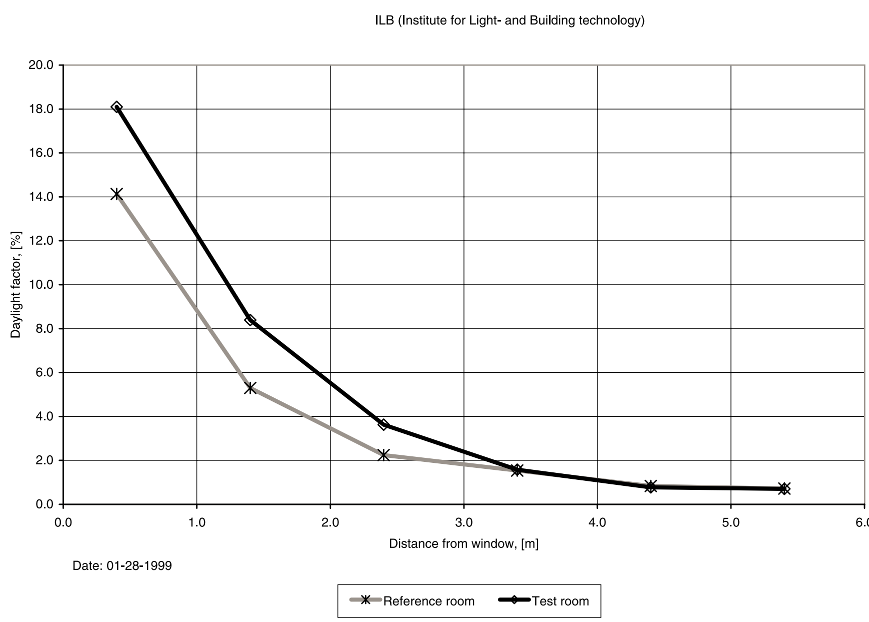
Figure 4-9.7: Interior view of the Geyssel office building in Cologne, Germany with sun-directing glass in the upper windows

Sun-directing glass Germany: 51°N Monitoring case and time	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	8.4%	5.3 %	1.6%	1.5%	0.7%	0.7%	8.0	3.3
Clear winter: Noon	1,514	510	607	344	329	249	24.6	67.3
Clear winter: 15:00	179	83	73	47	41	26	7.8	10.8
Clear equinox: Noon	1,570	680	840	388	574	285	60.4	70.1
Clear equinox: 15:00	908	360	432	213	273	155	44.6	41.7
Clear summer: Noon	1,971	1,213	753	614	502	365	79	54.0
Clear summer: 15:00	663	416	234	194	157	110	59	24.0

Note: The window, intermediate, and rear zone sensors were 1.4, 3.4, and 5.4 m the window, respectively. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing due south. DF% is the daylight factor.

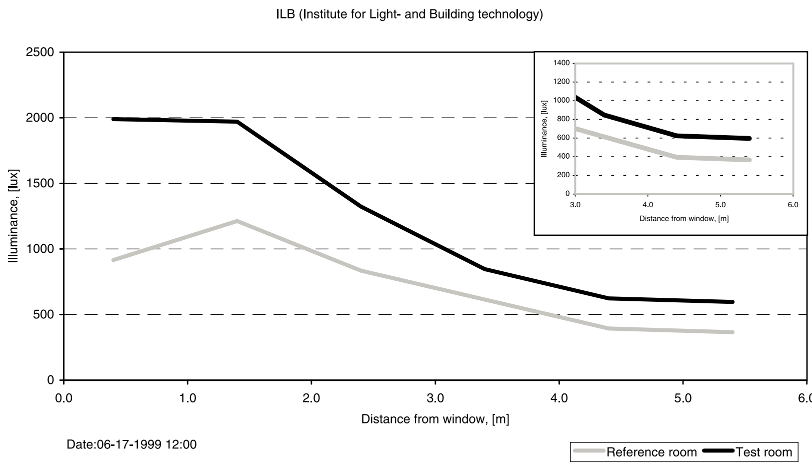
Overcast Sky

During overcast days, the sun-directing glass increases interior illuminance levels up to a 3 m depth from the window.



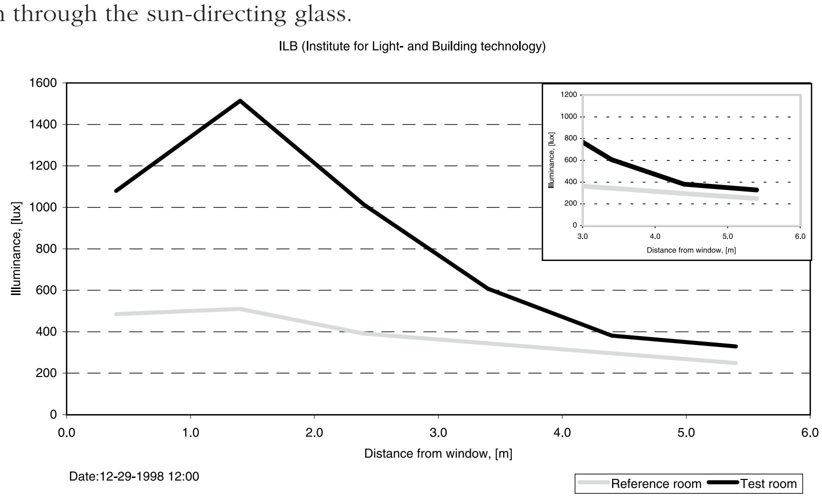
Clear Sky

At higher summer solstice sun positions, the illuminance level is sufficient in the whole room. A level of more than 500 lux was achieved even at the rear zone.



On the equinox, the illuminance level is sufficient in the entire room. Because the sun altitude is lower than in summer, the peak illuminance is located at a distance of 1.5 m from the window.

During winter, the illuminance level is much lower in both rooms than other times of the year because of decreased exterior illuminance. As a result of low sun positions, the venetian blinds' cut-off position to block direct sun is closed (80°) so that light can only enter the room through the sun-directing glass.



Conclusions (B)

As might be expected, the sun-directing system works best in sunnier climates and on building facades that receive direct sun. For overcast sky conditions or exposure to clear sky only, the effect of the sun-directing glass is small. The main improvement can be observed near the window with negligible impact beyond a distance of 3 m from the window.

On sunny days for the hours when the sun faced the building facade, the illuminance levels were often above 500 lux throughout most of a typical 5-m-deep room, allowing electric lighting to be dimmed or turned off. Compared to a conventional glazing system with partly closed blinds, the sun-directing system allowed higher illumination levels and relatively even daylight distribution. During winter, equinox, and summer, the sun-directing glass increased the illuminance in the back of the test room by 100 to 300 lux. Although a reference window without any blind system would have higher light levels if used as a reference case, it would also have very high illuminances from direct sun penetration and large potential glare problems.

During equinox and winter when solar altitude angles are lower, the redirected sunlight substantially increased illumination in the front two-thirds of the room and provided more moderate increases in the back of the room. In the summer months with higher sun altitudes, the sun-directing glass did not provide as much of a relative advantage as in the other seasons. Because sun-directing glass performance depends on solar altitude, it works best at mid-latitudes where the typical solar altitude is in the range of 15–65°.

In addition to providing more light throughout a space and enhanced light in the back of a room under given exterior conditions, the higher light levels resulting from sun-directing glass should provide better light balance throughout the space; thus, the technology should be easily accepted by users.

C. Sun-Directing Glass in a Clerestory Window (Germany)

Sun-directing glass covering the upper one-fourth (40 cm) of the vertical window was tested in unfurnished mock-up offices at the Technical University of Berlin (TUB, latitude 52°N, longitude 13°E). The sun-directing glass had a sinusoidal surface pattern on the interior surface of the window unit. It was installed vertically (interior to the existing double-pane

Figure 4-9.8: Interior view of the TUB test room with sun-directing glass (left) and reference room with clear, unshaded glazing (right) under overcast sky conditions

clear glazing) after determining that the depth of light penetration was nearly independent of sun position and the inclination of the glazing unit.

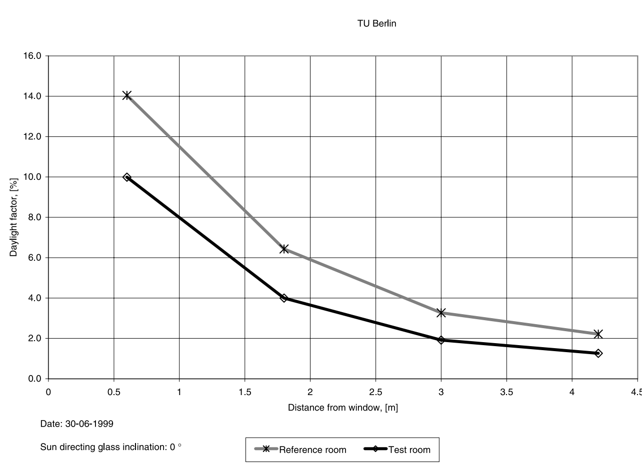
For the overcast sky measurements, the reference room had clear, unshaded glazing. For the clear sky measurements, exterior, diffuse-reflecting, light grey, 80-mm-wide, 45° tilted venetian blinds were extended over the full height of the window in the reference room and over the lower, 120-cm-high view window in the test room. In all other respects, the test and reference room windows were identical except for a 25-cm-high opaque frame that separated the test room's upper window from the lower view window (Figure 4-9.8). The interior ceiling was diffusing. A detailed test room description is given in Appendix 8.4.

Sun-directing glass Berlin: 52.47°N	Interior Illuminance Level (% or lux)						Exterior Conditions (klux)	
	Window Zone		Intermediate Zone		Rear wall Zone			
Monitoring case and time	Test Room	Ref. Room	Test Room	Ref. Room	Test Room	Ref. Room	Evg	Evgs
Overcast (DF%)	10.0%	14.0%	3.0%	4.9%	1.3%	2.2%	35	15
Clear equinox: Noon	2,540	1,240	1,330	840	710	520	65	61
Clear equinox: 9:00	1,650	860	920	530	520	320	46	37
Clear equinox: 15:00	820	440	490	290	270	200	33	32
Clear summer: Noon	1,450	800	890	530	500	330	99	55
Clear summer: 9:00	1,010	650	640	400	360	250	77	32
Clear summer: 15:00	640	380	370	250	210	170	74	31

Note: The window and rear zone sensors were 0.6 and 4.2 m from the window, respectively. The intermediate zone is an average of data taken at 1.8 and 3 m from the window. Evg (klux) is global exterior horizontal illuminance and Evgs (klux) is global exterior vertical illuminance on a surface facing south. DF% is the daylight factor

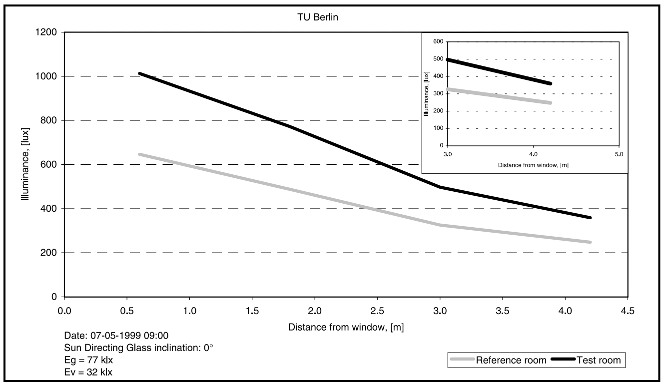
Overcast Sky

As expected, compared to a clear, unobstructed window, the sun-directing glass decreased interior work plane illuminance levels throughout the 4.5 m depth of the room. Towards the rear of the room, interior illuminance levels were reduced by ~39% compared to the reference case. The lower illuminance levels in the test room can be attributed to both the lower transmission of the sun-directing glass and the opaque 25-cm-high mullion that is used to divide the upper clerestory window from the lower view window in the test room.

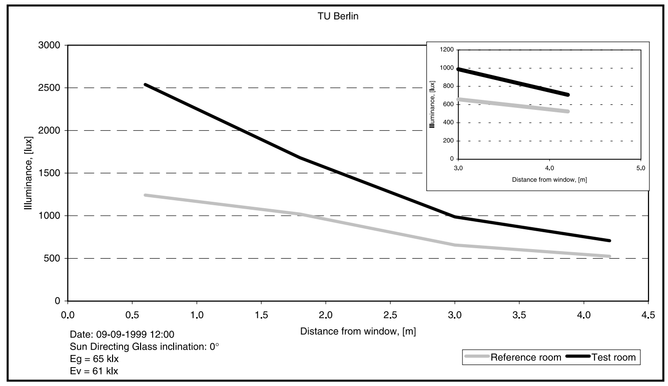


Clear Sky

Interior work plane illuminance levels in the test room were significantly greater than the reference room throughout the day for both the equinox and summer solstice conditions. No data were collected for the winter clear sky condition. Significant increases in illuminance levels occurred throughout the depth of the space. Light redirection was made apparent by the diffuse, upward-angled light patterns on the side walls (Figure 4-10.9). The large differences between the two rooms may be diminished with the use of a higher reflectance blind.



Summer, 9:00, Clear Sky



Equinox, 12:00, Clear Sky

Continuous surface luminance maps were made on clear days using a CCD camera. The luminance of the sun-directing glass varied between 2,000–10,000 cd/m^2 over the equinox and summer solstice days, compared to 800–600–1,800 cd/m^2 of the opaque portions of the grey venetian blind (direct views of the sky between the slats were comparable in luminance to the sun-directing glass). The sun-directing glass will create more direct source glare for some task locations and view angles.

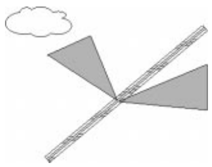
Figure 4-9.9: Luminance (cd/m^2) map of the TUB test room with sun-directing glass on September 9 at noon, E_{VG}= 46 klux, E_{VGS}= 37 klux.

Conclusions (C)

Under overcast sky conditions, the sun-directing glass decreased interior illuminance levels. Under clear sky conditions, interior illuminance levels were significantly increased compared to a grey venetian blind. The bright luminance of the sun-directing glass may cause glare.

Zenithal Light-Guiding Glass with Holographic Optical Elements 4.10.

Zenithal light-guiding glass redirects diffuse skylight into the depth of a room.



4.10.1. Technical Description

Components

The main component of zenithal light-guiding glass is a polymeric film with holographic diffraction gratings, which is laminated between two glass panes. The holographic element redirects diffuse light coming into the building from the zenithal region of the sky. Because the system may cause colour dispersion when hit by direct sunlight, it should only be used on facades that do not receive direct sunlight.

FIGURE 4-10.1: Outside view of zenithal light-guiding glass with holographic optical elements

Production

Zenithal light-guiding glass is produced when a holographic film is exposed to an interference pattern of two laser beams. After development, the pattern is fixed in the film as a periodic variation of the refractive index. The film is laminated between two glass panes for mechanical stability and protection against humidity.

Location in Window System

Zenithal light-guiding glass can be integrated in a vertical window system or attached to the facade in front of the upper part of the window at a sloping angle of approximately 45°. Because zenithal light-guiding glass slightly distorts view, it should only be applied to the upper portion of the window.

Technical Barriers

Zenithal light-guiding glass is designed for use with diffuse light only. If direct sunlight reaches the film, glare and colour dispersion may occur. Light-guiding holographic optical elements for direct light are under development.

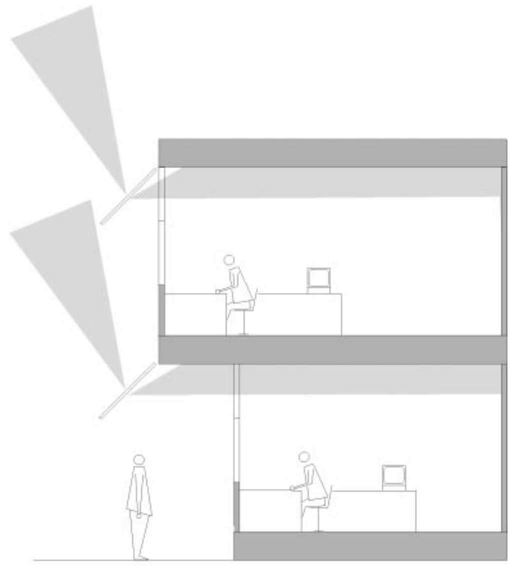


FIGURE 4-10.2:
EXAMPLE OF APPLICATION OF A ZENITHAL LIGHT-GUIDING ELEMENT

4.10.2. Application

Because zenithal light-guiding glass is integrated into the building envelope, architectural integration is required. The glass is installed in a building like a normal window or structural glazing unit. Installation does not require specific equipment or knowledge.

The system can be used in facades that are not exposed to direct sunlight. It is most useful in situations where the sky view is heavily obstructed (i.e., urban environments) and in cloudy climates with high sky luminances.

4.10.3. Physical Principles and Characteristics

The luminance level of the zenith region of the overcast sky is typically much higher than the level in the horizontal region, so zenithal light-guiding glass is a promising strategy for predominantly cloudy climates to redirect light from the sky zenith into the depth of a room [Kischkoweit-Lopin 1999]. Tilting the element at an angle of approximately 45° from the facade increases its exposure to the sky, so more light is redirected into the room. Thus, zenithal light-guiding glass is especially appropriate for buildings with external obstructions, e.g., in a courtyard situation.

The incident light from a specific area of the sky is diffracted by the grating in the refractive index of the holographic film and guided to the ceiling of the room. Because of the range of angles of the incident light, colour dispersion is mixed, so only small colour effects occur. When there is incident direct sunlight within the active angle of the element, glare occurs and colour dispersion cannot be prevented. Visibility through the holographic optical element is possible except in the general direction of the active angle.

4.10.4. Control

Zenithal light-guiding glass is a fixed daylighting system; therefore, no controls are required.

4.10.5. Maintenance

No maintenance is needed other than cleaning.

4.10.6. Costs and Energy Savings

A zenithal light-guiding system was installed for the first time in July 1996. The cost for the elements was about 900 euros per m^2. Prices may decrease with large-scale production.

Figure 4-10.3: Office with light-guiding element

4.10.7. Some Examples of Use

The first installation was in the ADO office building in Cologne, Germany. Zenithal light-guiding glass was attached to a north facade in front of three windows. A comprehensive evaluation of the ADO office building can be found in the IEA SHC Task 21 *Daylight in Buildings: 15 Case Studies from Around the World*.

Distance from the facade	0.2 m	1.2 m	2.2 m	3.2 m	4.2 m
Without HOE	15.78%	4.10%	1.35%	0.75%	0.57%
With HOE	14.71%	3.09%	1.40%	0.86%	0.72%

Table 4-10.1: Daylight factor with and without holographic daylight redirecting element

4.10.8. Simulations and Measured Results

The system has not been monitored in test rooms according to the IEA Task 21 monitoring protocols. The table above shows the daylight factor in an office with and without a holographic daylight-redirecting element. Although the system reduces daylight in the window area, daylight increases slightly in the depth of the room.

Holographic optical elements have shown promising laboratory results, but no significant energy savings have yet been demonstrated in a real building.

4.11. Directional Selective Shading Systems Using Holographic Optical Elements (HOEs)

Directional selective shading systems reject incident light from a small angular area of the sky vault. Thus, the system can redirect or reflect incident beam sunlight while transmitting diffuse light from other directions. This selective shading provides daylight to building interiors without seriously altering view from windows.

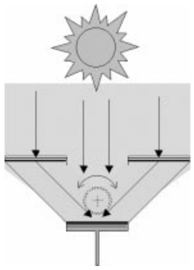


FIGURE 4-11.1: Holographic transparent shading system at REWE Supermarket Headquarters. above: Interior view of the glazed roof with external movable lamellas. below: Exterior view of movable lamellas

4.11.1. Technical Description

Components

Holographic diffraction gratings embedded in a glass laminate can be used in two different ways to provide shading control for large glazed areas.

In **Transparent Shading Systems,** the holographic optical elements are designed to directly reflect incident sunlight within a relatively narrow angular range normal to the surface. If the glass that incorporates these elements is rotated to follow the sun, direct sunlight is effectively shielded from entering the space while light incident from other angles passes through the system.

In **Sunlight-Concentrating Systems,** the holographic elements are designed to redirect and concentrate direct sunlight onto opaque stripes on a second set of glass elements. At these elements the sunlight is reflected, absorbed, or converted to electricity or thermal energy. This design allows the construction of a shading system that blocks direct sunlight while being transparent for diffuse light and viewers looking out.

In both designs, the whole shading element has to track the sun's path to achieve optimal shading, so a single-axis tracking system is necessary.

Production

The critical functional element in both types of directional selective shading systems is the holographic layer. A holographic film is exposed to an interference pattern of two laser beams. After development, the pattern is fixed in the film as a periodic variation of the refractive index. The film is placed between two glass panes for mechanical stability and protection against humidity. One or more glazings containing these holographic optical element panes are then integrated with other structural and tracking elements to create the linear modules described above.

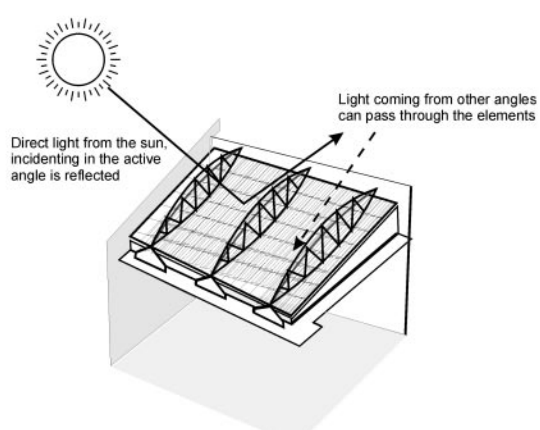


FIGURE 4-11.2: Roof application of transparent shading system at REWE headquarters in Cologne, Germany

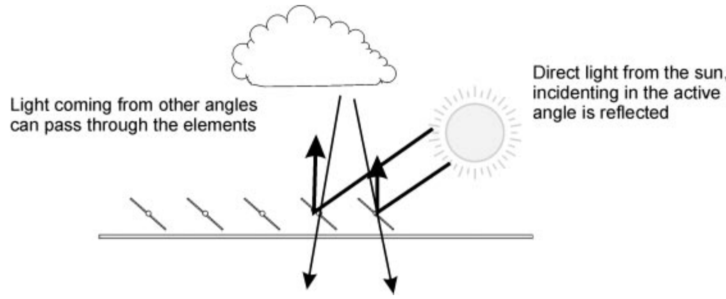


FIGURE 4-11.3: PRINCIPLE OF DIRECTIONALLY SELECTIVE SHADING IN A ROOF APPLICATION OF THE TRANSPARENT SHADING SYSTEM

Location in Window System

The movable glass element incorporating the holographic coating would normally be attached in front of the primary vertical glass facade or roof opening as a shading system. In some applications, these shading elements may be applied in the building's interior if solar gain can be vented through the roof structure; this arrangement reduces the weathering requirements for the single-axis tracking system. Whether on the interior or the exterior, the operable shading system needs to be integrated into the technical and architectural design of the building.

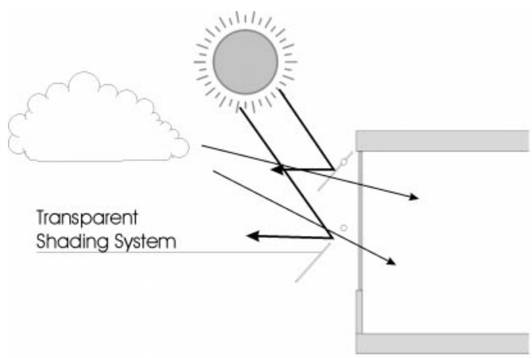


FIGURE 4-11.4: COMPUTER-GENERATED IMAGE OF SELECTIVE CONCENTRATING SHADING SYSTEM WITH HOLOGRAPHIC OPTICAL ELEMENT

Technical Barriers

Holographic optical elements are in the early stages of development; there is little long-term experience with their performance over time in harsh outdoor conditions. The mechanical systems that are needed to track and control the panels represent cost and maintenance barriers similar to those faced by other operable tracking systems.

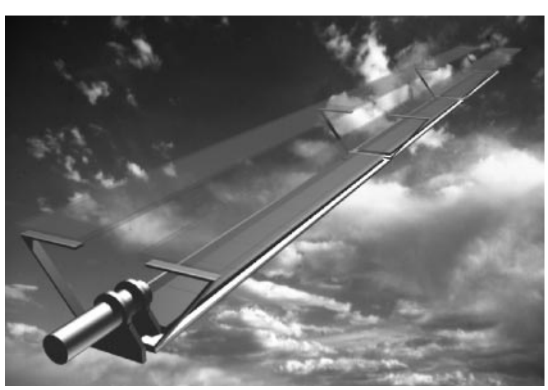


FIGURE 4-11.5: HOE TRANSPARENT SHADING SYSTEM

4.11.2. Application

The holographic optical elements are designed for use as a transparent shading system, which allows penetration of diffuse light for illumination purposes and good view out while blocking the intense rays of the direct sun. These elements are most applicable where a large glazed area is desirable but where glare or overheating from direct sun may be a problem. While many opaque operable shading systems are commercially available, these transparent shading systems have the potential advantage of maintaining a high degree of transparency for the overall building structure and providing good solar control. They can be installed to rotate about the horizontal or vertical axis, either on a vertical facade or over a glass roof. Colour effects may be caused by dispersion within the holographic optical element. With proper system design, this colour dispersion may not be noticed indoors unless the panels are not correctly aligned or adjusted.

Sunlight-concentrating systems utilise opaque elements to block direct sunlight. The opaque elements may directly reflect the light or light may be absorbed for thermal conversion and use, or absorbed by a photovoltaic panel for conversion to electricity. In these latter applications, there will be added integration requirements for the thermal conversion or photovoltaic systems [Müller 1996].

4.11.3. Physical Principles and Characteristics

Transparent Shading System (Total Reflection)

Incident light within the active angular range is redirected by the HOE at a very oblique angle towards the back of the glass laminate layer. After a ray bounces off the back glass surface by means of total internal reflection, the holographic layer redirects it back out the front surface. The holographic optical element is inactive for all other angles of incidence, so diffuse light can penetrate the HOE to provide daylight to the space behind the glazing. The view to the outside of the building is not significantly altered by the holographic element (Figure 4-11.1). For the system to operate at maximum effectiveness, the glass panel (which may have a horizontal or vertical axis) must track the sun's motion over the course of the day.

Sunlight-Concentrating System

Holographic optical elements redirect normal incident sunlight onto the opaque surface of a lower strip of glass or other material (e.g., photovoltaic), thus effectively blocking intense direct solar radiation. The holographic elements are optically inactive or transparent to all other angles of incidence, so diffuse light can penetrate through the elements to illuminate the building interior. The view out through the panels is reduced by the opaque strips (30 to 50% of glass area).

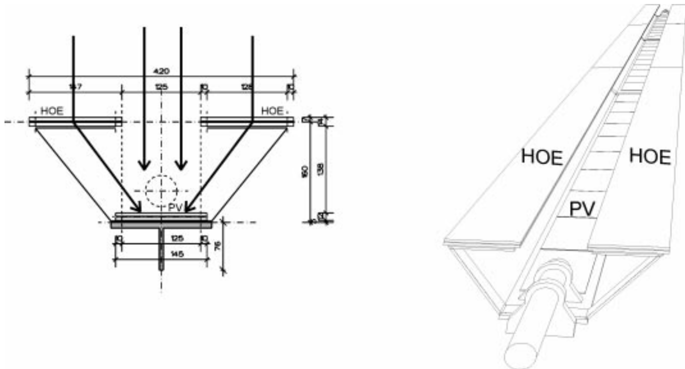


Figure 4-11.6: Advanced light-concentrating selective-shading lamella with solar cells. HOE = holographic optical element, PV = photovoltaic solar cells

4.11.4. Control

Both sunlight-concentrating and transparent shading elements have to track the sun's path. Tracking would normally be realised by a computer-controlled automated system similar to systems that operate motorised louvers. The sun's position can be pre-calculated and stored in a look-up table or directly determined with various lighting sensors. Generally the controls for such a system would be automated with some options for manual override.

4.11.5. Maintenance

The maintenance of the glass elements themselves involves infrequent cleaning in most environments. However, past experience has shown that maintenance of electromechanical systems to reliably operate a large number of movable glass panels is likely to be difficult.

4.11.6. Costs and Energy Savings

The cost of directional selective shading systems is high because the holographic elements are not yet produced in volume and the control systems are complex and costly. The first systems cost about 1,500 euros per square metre of the complete system including the cost of special mounting and tracking systems. Reliable energy savings figures are not yet available.

4.11.7. Some Examples of Use

Internationale Gartenbau-Ausstellung (IGA) Row Houses, Stuttgart, Germany – Light-Concentrating Shading Systems

The first generation of sunlight-concentrating systems incorporating photovoltaic (PV) cells was installed in 1993 and tested for three years at a demonstration building in Stuttgart. In 1996, new systems were installed using larger and cheaper PV elements. The sunlight-concentrating system used in row houses at the IGA has been shown to reduce temperatures in the courtyard area on sunny summer days. Figure 4-11.8 shows that the systems can control direct sunlight while admitting diffuse skylight on partly cloudy days.

REWE Headquarters, Cologne, Germany – Transparent Shading Systems

A first application of the transparent shading system is the courtyard of the REWE headquarters in Cologne (Figures 4-11.1, 4-11.2, 4-11.3 and 4-11.6).

Figure 4-11.7: Glazed courtyard of the REWE headquarters (Figure 4-11.1 shows more detail about this application of reflecting holographic elements)

4.11.8. Simulations and Measured Results

Directional selective shading systems have not yet been monitored in test rooms using the monitoring protocols of IEA SHC Task 21. Therefore, detailed performance data are not yet available for these systems. The solar transmission is 0.2 for the sunlight-concentrating elements and 0.27 for the transparent shading elements (both values for direct radiation only). In other words, these systems reject 70 to 80% of incident direct solar energy and reduce building cooling loads.

Measurements in the IGA row houses in Stuttgart and at REWE headquarters show that good shading control can be provided (for solar gain control) while good daylight illumination is maintained. The users at the two sites were satisfied with the lighting conditions, comparing them with sitting in the shade of a tree in summer.

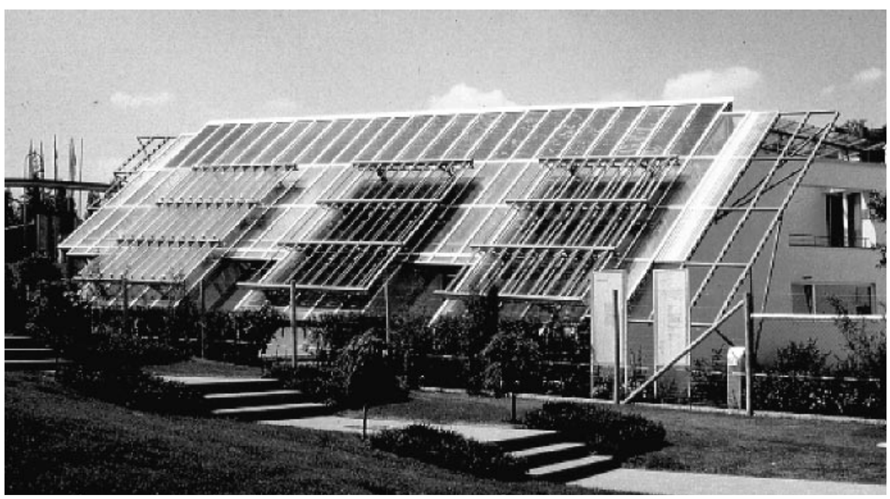
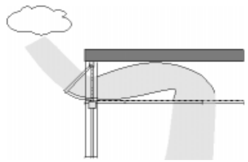


Figure 4-11.8: Sunlight-concentrating system applied at the IGA row houses in Stuttgart

Holographic directional selective shading systems of various designs may be used in any climate, but the greatest impact will be achieved in buildings with large glazed facades under sunny conditions. The transparent shading system is particularly useful where architectural requirements favour a transparent solar control solution rather than a conventional blind system. At the moment, the high cost and mechanical complexity of the tracking systems limit their use primarily to demonstration projects or high-profile buildings.

Anidolic ceiling systems use the optical properties of compound parabolic concentrators to collect diffuse daylight from the sky; the concentrator is coupled to a specular light duct above the ceiling plane, which transports the light to the back of a room. The primary objective is to provide adequate daylight to rooms under predominantly overcast sky conditions.



4.12.1. Technical Description

Components

An anidolic ceiling consists of daylight-collecting optics coupled to a light duct in a suspended ceiling. The system is designed for side lighting of nonresidential buildings. Anidolic (non-imaging) optical elements are placed on both ends of the light duct. On the outside of the building, an anidolic optical concentrator captures and concentrates diffuse light from the upper area of the sky vault, which is typically the brightest area in overcast skies, and efficiently introduces the rays into the duct. At the duct's exit aperture in the back of the room, a parabolic reflector distributes the light downward, avoiding any back reflection. The daylight is transported deeper into the room by multiple specular reflectors lining the light duct, which occupies most of the area above the ceiling. On sunny days, direct penetration of sunlight is controlled by a blind that can be deployed over the entrance glazing. The entire anidolic ceiling system is shown in schematic form in Figure 4-12.1.

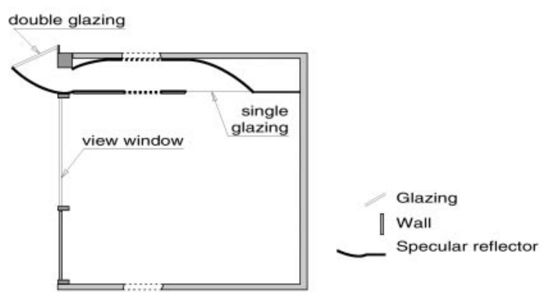


Figure 4-12.1: Schematic vertical section of an anidolic ceiling showing exterior anidolic collector, blind for sun control, specular duct in ceiling, and interior exit optics

Availability

Reflectors in the anidolic elements consist of anodised aluminium surfaces (reflectance $\rho = 0.9$) attached to shaped frames to produce the desired optical control. The prototype frames have been made of wood, but, if production volumes increase, other metal, plastic, or composite materials could be used. The ducts are enclosed by glazing to keep the reflective surfaces clean. The operable blind must be properly integrated into the system.

Location in Window System

An anidolic ceiling system is designed to be located on a vertical facade above a view window. Because the external anidolic device collects diffuse light rays with high optical efficiency, the anidolic ceiling is suitable for lighting rooms with diffuse daylight during overcast conditions. The system is designed to collect diffuse light from the sky vault, so it can be used in any latitude if solar blinds are installed to protect against glare and overheating from direct sunlight.

Technical Barriers

In its present application, the primary objective of the system is to provide adequate daylight under overcast sky conditions. In order to collect sufficient luminous flux, the anidolic collector must typically span the full width of the room facade, and the light duct must completely occupy the void above the suspended ceiling in the room. No other building systems or structural elements should be placed in this space. If they are, the luminous performance will decrease. In addition, because the use of anidolic ceilings directly affects many other building components, the use of this system requires additional coordination in planning and construction.

4.12.2. Application

The system is best used on vertical facades in buildings that are located in predominantly overcast conditions and that have limited access to direct sunlight or face obstructions in a large portion of the sky vault. Design requirements include:

- Available daylight must be efficiently collected from the sky vault and guided into the light duct, even during the worst overcast conditions (usually winter).
- Glare risks must be reduced by channeling the daylight from the facade into the room and redistributing it downward from the ceiling in a conventional manner (like electric light).
- Light duct dimensions must be compatible with available building space.

Channeling the light in a duct above the ceiling reduces the potential for undesired glare. When direct sunlight is the main daylight source, a high concentration factor is feasible, allowing a smaller duct system which will occupy less of the ceiling plenum (see Optically Treated Light Shelves, Chapter 4.3). Because the goal of the current application is to provide daylighting under overcast conditions and with the sky as a diffuse source, concentration is limited to a factor of 2 or 3 so a large light duct is required. The present design has been optimised on this basis, to accommodate a light duct that fills the entire ceiling plenum cavity.

Anidolic ceilings can be used in densely built-up urban as well as rural areas. Their relative effect is more impressive in an urban environment because obstructions around a building increase the importance of collecting diffuse light from the upper sky vault. Anidolic ceilings can be used in both clear and cloudy skies as long as proper shading is provided to control sunlight.

Anidolic ceilings can be used in commercial, industrial, or institutional buildings. Specific design solutions will vary with climate and latitude. Application to the renovation of buildings with deep ceiling plenum spaces or high ceilings may be appropriate if there are no large obstructions and interference with other building systems.

4.12.3. Physical Principles and Characteristics

The field of non-imaging optics has established reliable, efficient methods for designing solar concentrators, which have almost reached the theoretical limit of solar concentration (46,000 dictated by the law of thermodynamics [Welford and Winston 1989]). The same optical principles can be used to develop systems that maximise use of diffuse light from the sky vault (Figure 4-12.2). Features of such systems include:

- The “bundle size” of the light rays delimited at the entry aperture by the angles θ and θ' (given design parameters) is fully transmitted at the exit aperture. Existence angles include all hemispherical directions.
- The number of reflections can be minimised through an appropriate design (which explains the high optical efficiency achieved by the system).
- An accurate selection of incoming rays at the system’s entry aperture, as well as an accurate control of emerging rays at the exit aperture, can be achieved (high angular selectivity).

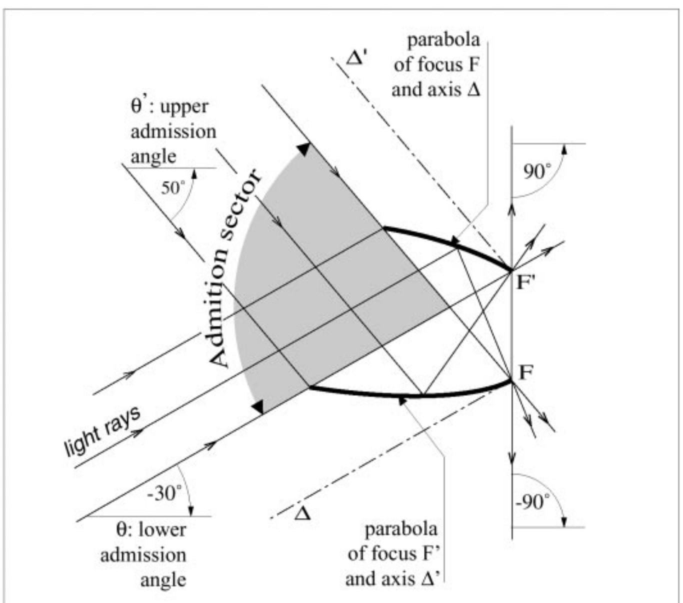


Figure 4-12.2: Principles of two-dimensional, non-symmetric anidolic system (Compound Parabolic Collector)

Because the system is based on reflection from a highly reflective surface (e.g., anodised aluminium), it does not introduce any optical dispersion, even with direct sunlight. The anidolic ceiling was developed with the above principles:

- an anidolic daylight collector was designed and placed in front of the light guide to collect and concentrate the daylight at the entrance of the duct;
- another anidolic device was installed at the end of the duct to distribute the flux of daylight into the room, so as to avoid visual discomfort.

When the sky is the light source, light concentration is essential for the anidolic ceiling system's performance. Although the concentration factor under overcast skies is limited to between 2 and 3, this is adequate for the desired interior daylight illuminance levels. At the interior end of the duct, light is "deconcentrated" by a second anidolic device to direct the flux towards the work plane.

4.12.4. Control

If an exterior blind is used to control direct sun and excessive glare, manual or automated controls are needed. The anidolic ceiling itself requires no additional controls.

4.12.5. Maintenance

The basic anidolic ceiling system typically needs no maintenance. In normal atmospheric conditions (i.e., not particularly dusty) and with typical air quality in an urban environment, rain is enough to clean the system's entrance pane to maintain normal performance levels. Operation of an anidolic ceiling system for approximately three years without significant performance losses has confirmed this (Figure 4-12.4). When a blind is installed for solar control, the blind system has to be maintained as well.

4.12.6. Costs and Energy Savings

The anidolic ceiling system requires additional first costs, relative to a conventional window, to create the optical collector system at the facade and to build the reflective plenum with the emitting optical element. We assume that blinds and lighting controls would be included in a conventional system, so these are not considered an additional cost. Energy consumption for electric lighting was monitored in two 6.6-m-deep identical mock-up offices (see Section 4.12.8A) equipped with the same dimmable light controller and suspended lighting fixtures (two rows of two 36-W fluorescent tubes). One room was fitted with the anidolic ceiling (test room) and the other with a conventional double-glazed facade (reference room). Both facades were unshaded and oriented due north during the monitoring period. Both rooms used clear glazings. The task illuminance (300 lux ± 15%) at 5 m from the window was balanced in both rooms by the continuously dimmable electric lighting control. Figure 4-12.3 shows results from monitoring lighting energy consumption. The office test room with anidolic ceiling used 31% less electricity for lighting during this monitored period than the reference office room for a conventional depth (6.6 m in the present case). Even greater relative savings could be expected in a deeper room.

These monitoring results agree well with the lighting savings figures calculated for this technology using the Swiss method for daylighting (ASE 8911.1989), which predicts yearly lighting savings of 30%. The Swiss method allows the statistical calculation of lighting energy use for a given required desk illuminance (300 lux in this case) on the basis of the daylight factor.

It must be emphasised that this savings figure assumes fully automatic control of the electric lighting (i.e., perfect daylight-responsive dimming), independent of user behaviour. Depending on user behaviour, the utilisation of solar blinds as well as lighting control can lead to different results, especially for south-oriented or other facades that receive direct sunlight.

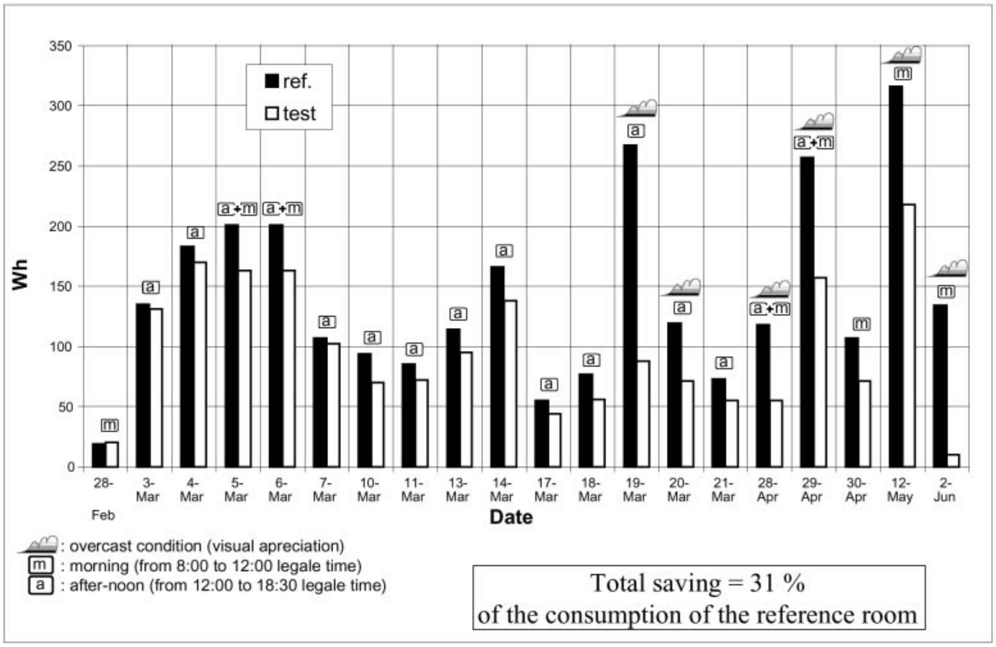


Figure 4-12.3: Lighting energy consumption monitored in the test and reference rooms from February to June (both rooms are equipped with the same dimming controller)

4.12.7. Some Examples of Use

- Module de demonstration en éclairage naturel (DEMONA) daylighting test modules, Lausanne, Switzerland
- LESO Solar Experimental Building, Lausanne, Switzerland

See the following section for monitored results from these two examples.

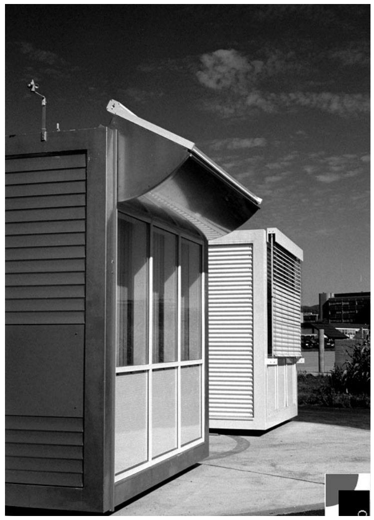
4.12.8. Simulations and Measured Results

A. DEMONA Daylighting Test Modules (Switzerland)

An anidolic ceiling was installed in a 1:1 scale office test module and was placed next to a reference module equipped with a conventional double-glazed facade. The modules had identical interior photometric properties (ρ_{walls}=0.80, $\rho_{ceiling}$=0.80, ρ_{floor}=0.15) and identical dimensions (3.05 x 6.55 x 3.05 m). Figure 4-12.4 gives a front view of the two modules, placed on a rotating circular platform and facing the same direction. More information about these test rooms can be found in Section 8.4 and Courret [1999].

The anidolic system used an insulated double low-E glazing (visible transmittance of 0.81) at the entry aperture for thermal reasons. The entrance pane had a tilt angle of 25°,

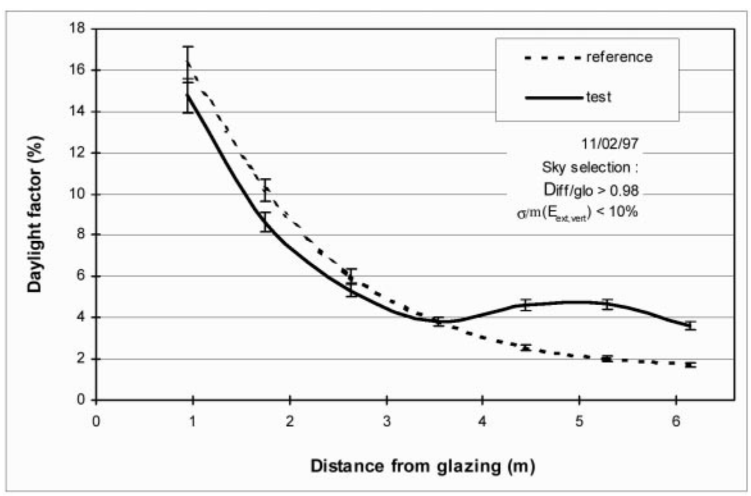
Figure 4-12.4: Front view of the two daylighting modules. Foreground: test module (anidolic ceiling); Background: reference module (double-glazed facade with blinds lowered). This south-facing, shaded configuration was not used for the test results shown here



which contributed to its cleaning by rainfall and provided a more favourable incident angle for light rays from the upper sky dome (the bright part of the sky). All the external parts of the system were thermally insulated to avoid thermal bridges and water condensation. A single clear plastic panel (visible transmittance of 0.9) was placed at the interior ceiling exit aperture for maintenance purposes. The system, built in 1996, has shown no significant degradation of performance or mechanical troubles during a period of three years.

In the test room with the anidolic system, the daylight factor on the work plane at 5 m from the window is more than double the value in the reference room under overcast conditions. Both rooms had no exterior or interior shading and both rooms had clear glass. The rooms were oriented due north. The average daylight factor in the back half of the rooms is improved by a factor 1.7 to reach more than 4% in absolute value. In an urban environment with obstructions of 40° elevation, simulation results show that this improvement ratio could reach 2.8. The uniformity of daylight distribution is improved because the overhang of the anidolic system reduces light levels in the front of the room (CIE uniformity ratio goes from 0.3 to 0.6). More extensive data on the overall performance of the system can be found in Courret [1999].

Figure 4-12.5: Comparison of daylight factor profiles in the test room (anidolic ceiling) and in the reference room (double-glazed facade) under overcast skies. The average and standard deviation shown on the graph represents a sample of 43 separate measurements within a period of 40 min.



In addition to the lighting monitoring study, human factors tests were carried out on a group of 33 subjects in the same two test rooms. For these studies both modules were oriented due south. This orientation was chosen to take into account possible glare risks from direct sun penetration into the modules. Furniture, desks, and VDTs were identical in both rooms to permit an objective comparison of the luminous work environment in the two modules.

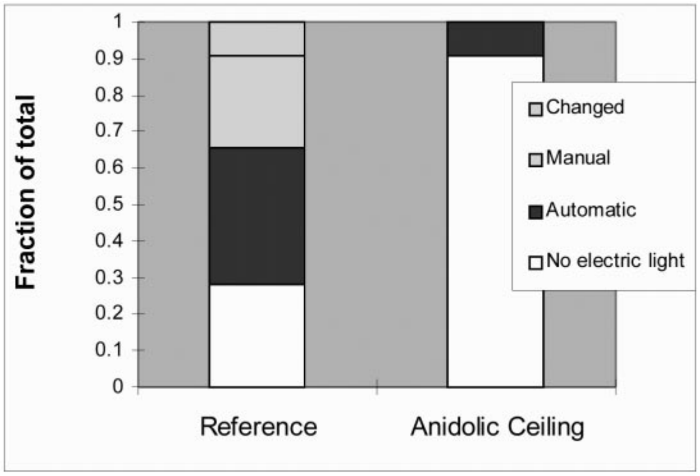


Figure 4-12.6: Lighting mode used by the subjects in the different rooms (subjects could choose lighting modes at their convenience)

The work planes were located in the rear of the rooms 5 m from the window. Their orientation was chosen so that the main view axis of the occupants was parallel to the window. The occupants were provided with varying degrees of control over the electric lighting. The electric lighting system is described in Section 4.12.6. Three different types of response tests were conducted:

- a test of acuity based on black/white document reading,
- a test of acuity based on VDT reading,
- a questionnaire on user acceptance.

The acuity test for document reading showed that a subject makes, on average, 38% fewer reading errors in the room with an anidolic ceiling than in the reference room. Analysis of the lighting/daylighting modes chosen by the subjects showed a considerable difference between the two rooms. In the test room with anidolic ceiling, daylight was strongly preferred as the light source (Figure 4-12.6). In the reference room, occupants selected a variety of electric lighting control strategies.

The acuity test for VDT reading showed that less luminance contrast is necessary to read a number on a VDT screen in the test room than in the reference room (a 10% lower contrast threshold). This tendency is consistent with the assessment of visual comfort, suggesting that visual performance enhancement is probably the result of a more appropriate luminance ratio of the surroundings to the VDT screen in the test room.

The user acceptance questionnaire was the basis for comparison of the perceived visual atmosphere in the two rooms. The study concluded that:

- The visual atmosphere was perceived to be brighter in the test room.
- The colours in the test room were found to be more pleasant although they were physically the same as those in the reference room.

The anidolic system provides improved control of daylight distribution in a room relative to a conventional window. Measurements were made under an overcast sky as well as sunny conditions with the blinds pulled down both for the view glazing and at the entrance of the anidolic collector. Luminance scanning at the work plane in the rear of the offices showed that:

- The anidolic ceiling contributed to a more uniform luminance distribution on the walls and ceiling, thus slightly improving the perceived luminous environment at the desk (lower luminance gradient).
- The additional daylight flux brought in by the anidolic ceiling improved the luminance ratio in the field of view (ratio closer to unity).

These two effects significantly increase visual comfort for reading tasks involving paper as well as VDTs.

Conclusion (A)

By introducing additional daylight in the back of the room, the anidolic ceiling improves overall light levels as well as uniformity from front to back. The absolute figures achieved by the system (a daylight factor of more than 4% at a distance of 4 to 6 m from the facade under overcast conditions) are better than those for most existing side lighting systems. With appropriate electric lighting controls, this system can produce significant lighting energy savings, especially for climates dominated by overcast conditions. Studies with building occupants have demonstrated improved working and lighting conditions, which may translate into better productivity and visual amenity for users.

Figure 4-12.7: View of the renovated south facade of the LESO solar experimental building with its external anidolic system

B. LESO Solar Experimental Building (Switzerland)

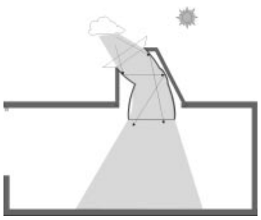
The LESO solar experimental building is a mid-size non-residential building (780 m^2 of heated floor area), which hosts researchers at the Solar Energy and Building Physics Laboratory (LESO-PB) of École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. The building was built in 1980-81, using principles of energy conservation and passive solar design; it is characterised by a thermally insulated envelope and a highly glazed south facade (200 m^2), which collects passive solar energy during the winter.

The facade was fully renovated in 1998-99. On the south facade, the existing glazing was replaced with insulating double glazing that has a selective coating (U=1.1 W/m^2K) and, on three building floors, 25-m-long anidolic collectors were installed, similar to the one described earlier. The upper and lower glazing have blinds to provide shading and sun control when needed.

Because of the rather shallow depth of the offices (less than 4.5 metres deep) at EPFL, the use of a ceiling light duct was not considered appropriate. Instead, diffuse daylight along with sunlight collected by the device are redirected towards the ceiling instead of being sent through the duct. Under overcast conditions, a daylight factor of 2% is achieved at a distance of 3.5 m from the facade, comparable to the performance of a more conventional facade, but the system provides more uniform daylight distribution in the room than a conventional facade would.

Anidolic Zenithal Openings 4.13.

The anidolic zenithal opening is a daylighting system based on non-imaging optics. This anidolic device's high angular selectivity (see Chapter 4.12) is used to collect diffuse daylight from a large portion of the sky vault without allowing direct sun penetration. This form of skylighting system is best utilised to provide daylight to single-storey buildings, atrium spaces, or the upper floor of multi-storey buildings.



4.13.1. Technical Description

Components

The anidolic zenithal opening system is composed of an optical concentrating element and a "deconcentrating" or emitting element. The collector is based on a linear, two-dimensional, non-imaging, compound parabolic concentrator whose long axis is oriented east-west. The opening is tilted northward for locations in the northern hemisphere and designed so that the sector where it admits light includes the whole sky between the northern horizon and the highest position of the sun in the southern sky during the year. As shown in Figure 4-13.2, the sun never comes inside the admission sector, except at the beginning and end of the day, between the spring equinox and the autumn equinox. Solar protection is completed with a series of vertical slats uniformly laid over the aperture and spaced at 0.5 m.

Figure 4-13.1: Scale model of an anidolic zenithal opening located on a roof

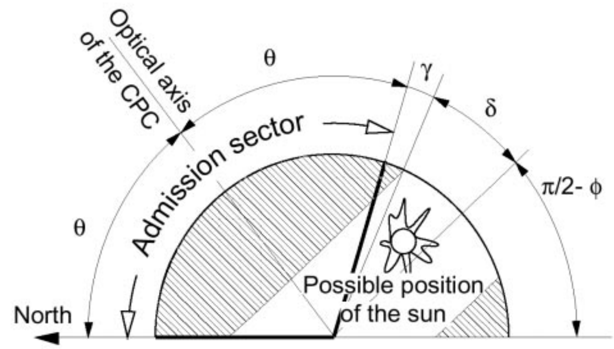


Figure 4-13.2: Admission sector of an anidolic zenithal opening designed for 47°N; φ is the latitude (47°N), δ the maximal declination (23.5°), and γ an arbitrary angle

The admission angle, θ, is equal to 50°, and the tilt angle, α, from the horizontal is equal to 40° (see Figures 4-13.2 and 4-13.3). These angles can be determined using a simple equation given in Courret [1999] and depend on the latitude of the site (47°N in this case).

A compound parabolic deconcentrator, similar to the compound parabolic concentrator mentioned above but reversed, is placed at the emitting end of the opening to guide the daylight flux towards the bottom of the room. In the situation illustrated in Figure 4-13.3, it points vertically downward. The connection between the concentrator and deconcentrator is made with a section of cylindrical reflector. The whole device makes up the anidolic zenithal opening shown in Figure 4-13.3. The exit angle of the device, θ_d, is equal to 40° and is truncated at 45° to reduce its length. The anidolic zenithal opening does not constitute a direct glare source for building users under normal circumstances. In order to prevent the reflectors from gathering dust, the device is enclosed between two layers of glazing (visible transmittance of 0.9).

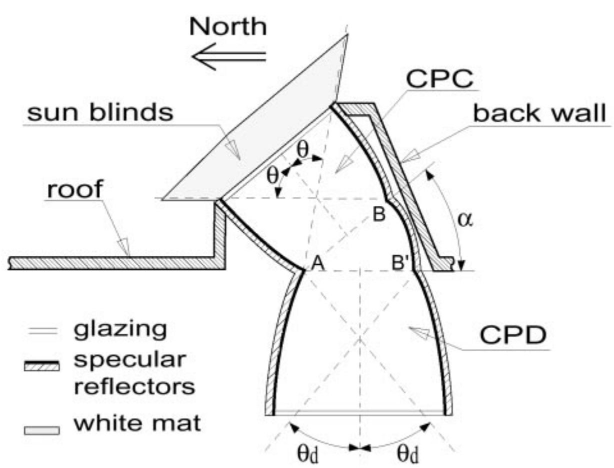


Figure 4-13.3: Cross-section of an anidolic zenithal opening

Production

The reflector surfaces consist of sheets of anodised aluminium (specular reflectance of 0.9), which are placed on shaped frames made of wood or other structural materials. With the economics of volume production, the frame could be made of a composite material, for example fibreglass/epoxy, coated with a film of anodised aluminium. The specular reflective surfaces must be protected during the construction process. No extra precision is needed in construction and assembly compared to what is required by conventional building practises.

Location in Window System

This system is designed to be located in roofs with an east-west longitudinal axis. Its entry aperture is tilted to the north in the northern hemisphere and to the south in the southern hemisphere (see Figure 4-13.4).

Technical Barriers

The anidolic zenithal opening must be designed as part of a roof system over a task area or atrium space, so the system must be integrated into the building design process in its early stages. Construction details such as sealing and waterproofing would be similar to those for other rooflighting systems.

4.13.2. Application

The anidolic zenithal opening is designed for roof applications. Like any roof opening oriented to the north (in the northern hemisphere), this device has the advantage of providing daylight that is only weakly dependent on changes in the luminance distribution of the sky resulting from motion of clouds or the sun. Because the luminous output will not vary as widely as that of systems admitting direct sunlight, the anidolic zenithal opening should produce less glare and provide improved visual comfort. It should thus find favour in applications where there are clear indoor spaces for which visual comfort is essential (e.g., sport halls, museums, atria, and markets). It may, however, require larger aperture areas than systems that are designed to admit direct sunlight.

4.13.3. Physical Principles and Characteristics

The system design is based on non-imaging optics and is similar to the design of any anidolic daylighting system. A more detailed description of the underlying optical principles is given in Chapter 4.12. (Anidolic ceiling).

4.13.4. Control

Anidolic zenithal openings provide efficient protection against direct solar radiation without using movable parts. This protection has been demonstrated in tests on a scale model. Even though anidolic zenithal openings have no moving parts, the daylight they transmit throughout the year should be less variable than that transmitted by either fixed or movable systems that must control direct sunlight.

4.13.5. Maintenance

Because anidolic zenithal openings have no movable parts and because image transmission is not an issue, they have no particular maintenance issues. Under normal atmospheric conditions (i.e., not particularly dusty) and in a middle-latitude, European rainfall should be sufficient to clean the entrance glazing.

Table 4-13.1: Daylighting autonomy (%) calculated from mean daylight availability under overcast skies in Switzerland. Opening ratio is the ratio of glazing area to total roof area

opening ratio (%)	10			15			20			25			30			35			40		
Shed with blinds	10	0	0	45	5	0	60	25	0	65	40	5	75	50	20	80	60	35	82	65	45
Shed without blinds	30	0	0	60	25	0	70	45	10	80	60	30	82	65	45	84	72	55	85	75	60
Anidolic systems	55	20	0	74	52	25	82	65	45	85	75	65	87	80	65	88	82	72	89	84	75

lighting need: 300 Lux 500 Lux 750 Lux

4.13.6. Costs and Energy Savings

In temperate climates, overcast sky conditions occur frequently, particularly in the winter, spring, and fall. Under these conditions, an adequate daylight factor is necessary to achieve lighting energy savings. The efficiency and optimisation of light transmission, however, should not take priority over visual and thermal comfort. Anidolic zenithal openings were compared to two types of conventional skylight systems: horizontal diffusive glazing and sawtooth roof glazings [Courret et al. 1996] using computer simulations. "Daylighting autonomy" was calculated for different opening ratios and lighting set points (mean horizontal illuminance) for each of these three designs. Daylighting autonomy is the percentage of time when the overcast sky is sufficiently bright to enable the electric lights to be switched off during the working hours of 8:00–18:00. If one multiplies this parameter by the time frequency of overcast sky conditions and lighting power consumption, one can obtain an estimate of annual lighting energy use. The results are presented in Table 4-13.1. In order to achieve a task illuminance of 500 lux with a 50% daylight autonomy an opening ratio of 30% of the roof area is required with clerestories ("shed with blinds"); with anidolic openings, the required ratio is only ~15%.

Under clear sky conditions and in a semi-temperate climate (Geneva) with a 20% opening ratio, interior daylight levels reach 500 lux during 79% of the hours of building occupancy.

4.13.7. Some Examples of Use

An anidolic zenithal opening was incorporated into the design for the atrium of the new building for the Archives Cantonales du Tessin in Switzerland. In order to integrate the opening into the roof, several modifications were needed because the atrium was not oriented east-west. A cross-sectional view, shown in Figure 4-13.4, gives the overall proportions. In the original building design, daylight was provided only by a series of vertical windows placed at the top of the atrium. Introducing the anidolic zenithal opening increased the horizontal illuminance at the bottom of the atrium by 64%; the opening ratio increased by only 11%. Although these design studies appeared favourable, the anidolic zenithal opening was not incorporated into the final building design.

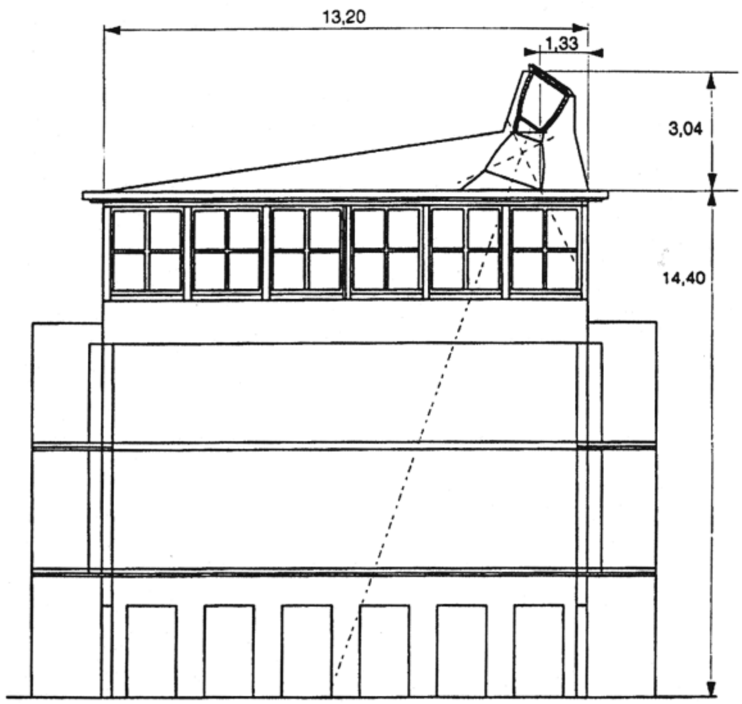


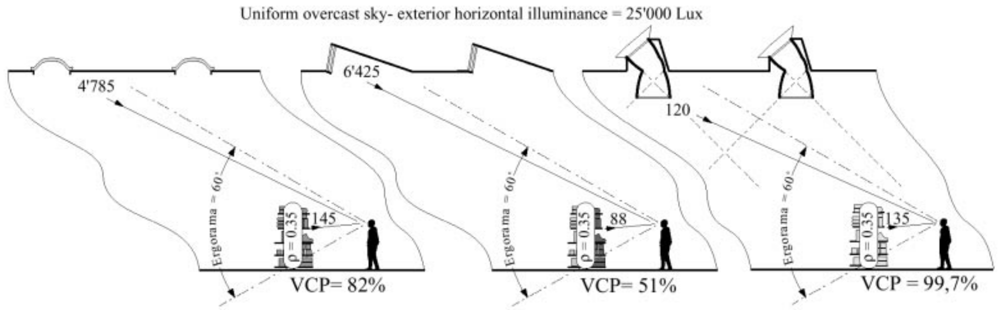
FIGURE 4-13.4: CROSS-SECTION OF THE ATRIUM OF THE ARCHIVES CANTONALES DU TESSIN (SWITZERLAND) WITH AN ANIDOLIC ZENITHAL OPENING INCORPORATED INTO THE DESIGN

4.13.8. Simulations and Measured Results

Potential application of an anidolic zenithal opening to a 10 x 15 x 7-m test building has been studied through numerical simulations [Courret et al. 1996]. A roof opening utilising an anidolic zenithal opening provides twice as much daylight on a horizontal task as is provided by vertical clerestories of similar size. The anidolic zenithal opening's daylighting performance is equivalent to that provided by a horizontal diffusing skylight aperture with a 58% transmittance. However, unlike with a conventional skylight system, the anidolic zenithal opening prevents overheating from sun penetration.

Anidolic zenithal openings can provide required illuminance without excessive glare at the ceiling level. For example, as shown in Figure 4-13.5, the anidolic zenithal openings with a luminance value of 120 cd/m^2 are not brighter than the task in the working area (contrast ratio approximately equal to 1). This is not the case in the two other situations where the brightness ratio for the diffusive horizontal glazing and the sawtooth rooflights are 30 and 70 times brighter, respectively, than the tasks in the field of view. The skylight luminance levels could be reduced with a light well; however, in that case, daylight illuminance would also be reduced.

Figure 4-13.5: Guth's visual comfort probability for three alternative roof light designs (luminance values in cd/m²)

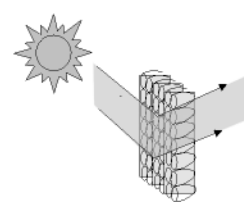


Conclusion

The anidolic zenithal opening applies the principles of non-imaging optics to skylight systems to produce a design that provides adequate illuminance levels by capturing diffuse sky light from a northerly sky view. The optical design of the device offers efficient protection against direct solar radiation transmission throughout the year without use of movable parts. The performance of the system was validated using scale-model tests. Numerical simulations show that this type of roof opening can be twice as efficient as vertical clerestories of similar size. Daylight autonomy of 50% is achieved for 500-lux illuminance levels using only a 15% glazing opening/roof ratio. The daylighting performance of the anidolic zenithal opening is equivalent to that of a horizontal aperture covered with a 58% transmitting diffusive glazing, but the anidolic zenithal opening has the added advantage that overheating from sun penetration is prevented. The anidolic zenithal opening provides better glare control and improved visual comfort than conventional skylights. It should thus find favour in applications where there are clear indoor spaces in which visual comfort is essential (sport halls, museums, atria, and markets, for instance). Because anidolic zenithal openings must be properly integrated into a building's design, they must be considered early in the design process.

4.14. Anidolic Solar Blinds

Anidolic solar blinds consist of a grid of hollow reflective elements, each of which is composed of two three-dimensional compound parabolic concentrators. The blinds are designed for side lighting and provide angular-selective light transmission to control sunlight and glare. The design is, at present, in the prototype and demonstration phase.



4.14.1. Technical Description

Components

The innovative feature of anidolic solar blinds compared to other anidolic systems (anidolic ceilings, anidolic zenithal openings) is their use of three-dimensional reflective elements (see Figure 4-14.1) and their small scale. The optics of the admitting portion of the blinds are designed to reject most high-solar-altitude rays from direct sun but to transmit lower-altitude diffuse light or winter sunlight. Figure 4-14.1 shows the fraction of rejected rays as a function of altitude and azimuth. The design of the portion of the blinds that admits light can be adapted to the specific facade orientation and the typical diurnal cycles of the outdoor temperature (e.g., more solar penetration is needed before noon than after). The optics of the portion of the blinds that emit light are designed to direct daylight into the upper quadrant of the room towards the ceiling and to spread the light horizontally within ±25° of the window surface normal. This design helps diffuse the transmitted sunlight without creating glare.

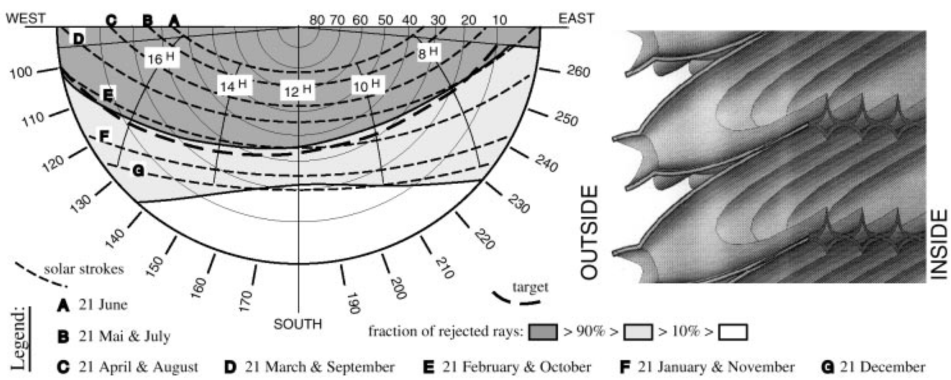


Figure 4-14.1: Comparing desired and calculated fraction of rejected rays (left); section of three-dimensional computer model of anidolic solar blinds (right)

Production

The elements of the blind system can, in theory, be produced at any scale (greater than daylight wavelength) and should be optimised for each latitude and orientation. In the present study, the facade is assumed to face due south (latitude 47°N).

Computer simulation based on ray tracing was used to assess the final performance of the device, whose shape had to be modified to fulfil the manufacturing requirements (laser stereo-lithography). The transmittance of the anidolic solar blinds was also assessed experimentally by means of an integrating sphere. The angular selectivity of the device with regard to the different possible directions of incoming rays was also evaluated.

A series of 20 pieces (31 x 35 x 10 cm) of 48 hollow elements each was manufactured in plastic by means of "vacuum cold moulding" in a mould of silicon. The initial "mother" piece was created through laser stereo-lithography from a computer model. Mirrored surfaces were created by depositing an aluminium coating by vacuum vapour deposition. Figure 4-14.2 shows the appearance of a section of the blinds.

Location in the Window System

The anidolic solar blind system can be applied either as a fixed louver to window openings that were principally designed to collect daylight (i.e., the view through them is blurred), or can be placed in the upper part of a normal window if view to the outside must be maintained through a lower portion of the window. In either application, anidolic solar blinds would typically be placed between two panes of glass for protection against dust.

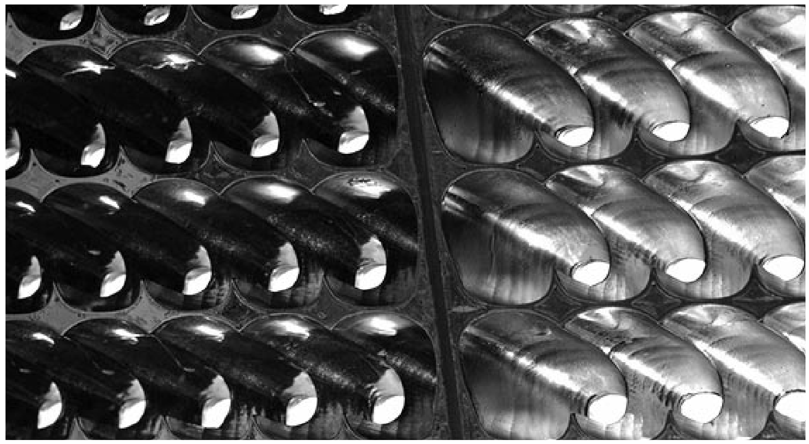


Figure 4-14.2: Photograph taken behind the exit aperture of the device. A cell looks bright only if the view direction belongs to the emitted angular sector

Technical Barriers

A number of production problems have to be solved before the system could be readily available at low cost. An efficient process would have to be developed to translate the design criteria for a particular application into the mould and then to produce the final product in large panels. Improved methods of applying and maintaining the reflective coating are also needed.

4.14.2. Application

Anidolic blinds are a fixed system to control daylight and thermal gains in south-facing or other facades that receive extensive sunlight. The blinds are intended to increase daylight penetration under a wide range of conditions while preventing the interior space from overheating. They do not use any moving parts. Although the system is mainly designed to control daylight in sunny climates, it may be used under predominantly cloudy skies.

4.14.3. Physical Principles and Characteristics

The system design is based on non-imaging optics and is similar to other anidolic systems except that it is made of three-dimensional elements. A more comprehensive description of non-imaging optics is given in Chapter 4.12 (Anidolic Ceiling) and in Courret [1999].

Experimental results (see Figure 4-14.3) show that the anidolic solar blind system's maximum transmittance reaches 26% in the central part of the admitting zone. This value corresponds to the ratio of the effective areas of the apertures for the most favourable angles of incidence. The discrepancy between theoretical and measured angular selectivity is mostly a result of the process of producing the prototype.

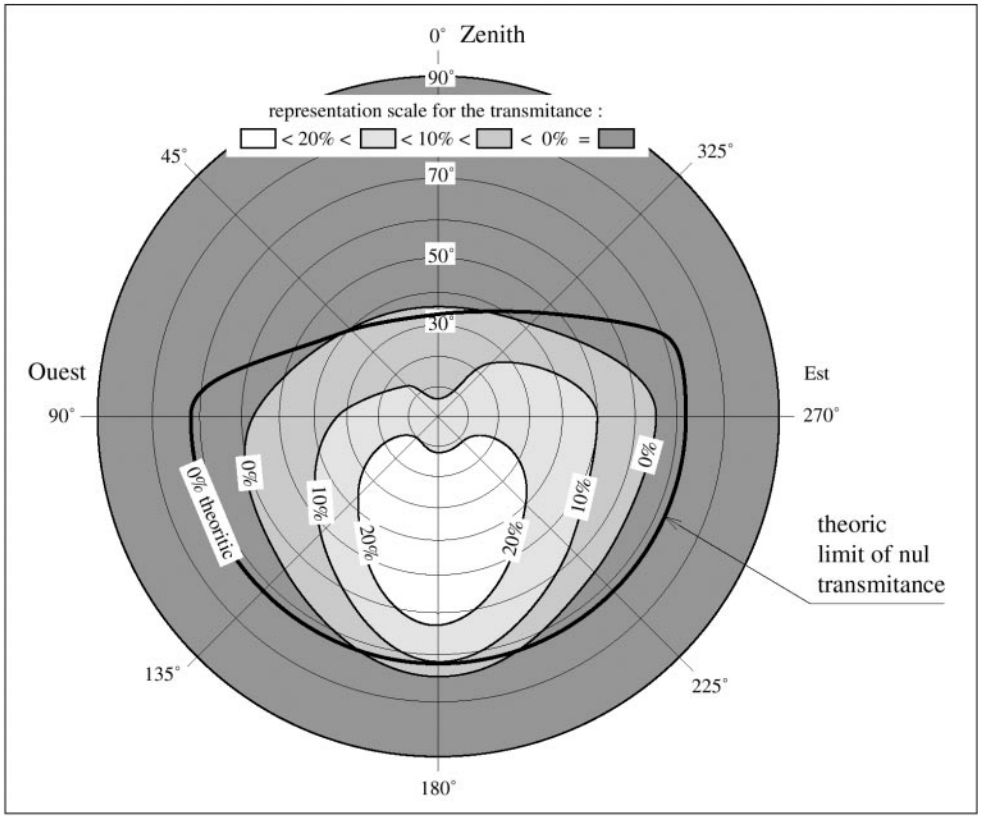


Figure 4-14.3: Comparison of measured and theoretical angular admission selectivity of a three-dimensional anidolic window element (height angle is relative to the normal of exit aperture; azimuth is relative to the vertical side of the prototype)

4.14.4. Control

The anidolic solar blind system is explicitly designed to control sunlight penetration for specified sun positions (see Technical Description above and Figure 4-14.1). It can remain in a fixed position and does not have to be moved like a conventional fabric or lamella blind.

Solar gain or illuminance levels can be increased by tilting the device from its vertical position. This possibility was tested experimentally (18° upward tilting), and performance improvements were confirmed.

4.14.5. Maintenance

Because the anidolic blind is a fixed system that is protected against dust and dirt by glazing on both sides, no particular maintenance is required.

4.14.6. Costs and Energy Savings

Because of its performance requirements, the system's required three-dimensional shape is more complex than two-dimensional anidolic systems such as the anidolic ceiling and the anidolic zenithal opening. Cost depends largely on the details of the manufacturing process. The current device could, in principle, be designed and manufactured with a high degree of automation and mechanisation, resulting in cost reductions. The manufacturing process for anidolic solar blinds is more complex, and the cost for this device is therefore likely to be higher than for the other devices. However, because the optics of anidolic solar blinds should function at almost any scale, the possibility remains that the solar blind panel could be made at large volume and low cost.

Primary energy savings are achieved by controlling electric lighting energy use when daylight from the anidolic blind is available. Greater energy savings can be expected from use of direct sunlighting than from diffuse daylighting. Because the problem of glare is solved by redirecting light to the ceiling, the blinds can also provide substantial heat gain in winter without adverse visual impact. Their very efficient summer-shading function reduces air-conditioning energy consumption as well as peak installed cooling capacity and peak power requirements.

4.14.7. Some Examples of Use

Anidolic solar blinds have not yet been used in a building.

4.14.8. Simulations and Measured Results

Simultaneous daylighting measurements were taken in side-by-side 1:1 full-scale test rooms to assess the comparative performance of the solar blinds. The two test modules were each 6.5 m deep and 2.65 m high. The mock-up office rooms have identical photometric properties (r_{walls}=0.8, $r_{ceiling}$=0.8, r_{floor}=0.15), which correspond to good room lighting design (2% daylight factor deep in the room for the reference module).

The reference test room utilised a high-quality white venetian blind whose slat tilt angle increases from top to bottom to allow penetration of daylight while simultaneously protecting work spaces from sun penetration and glare. The venetian blind slats were set to provide the same solar protection as the anidolic device (e.g., no penetration of sun rays with an incidence angle of more than 45°). A set of seven horizontal illuminance sensors was placed along the centre of each room at desk height.

Clear Sky

Light levels were low near the front of the room because the roller blind obstructed the lower two-thirds of the window. The illuminance increased in the rear of the room thanks to the deflecting function of the anidolic elements and the reflections on the ceiling and back wall. This enhancement meant that light levels measured in the front part of the room equal those in the back (Figure 4-14.4).

The illuminance level was lower in summer (corresponding to a 65° solar altitude) than in winter (corresponding to a 29° solar altitude), so the desired seasonal selectivity was clearly achieved.

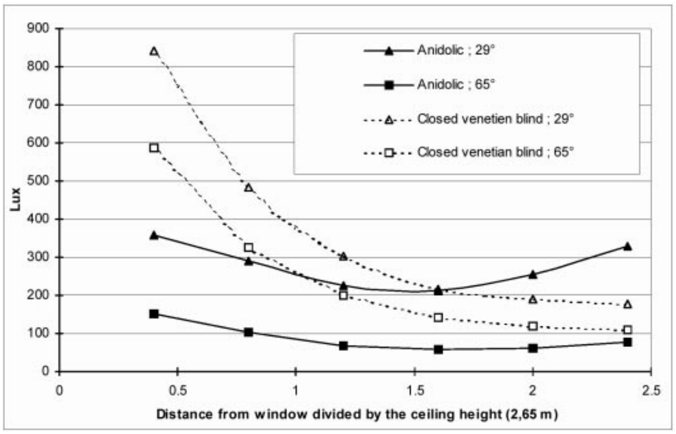


Figure 4-14.4: Indoor illuminance for two solar altitudes, 29° and 65° (sun azimuth = 0°) under clear sky conditions. The illuminance on the facade reached 85 and 41 klux, respectively.

Comparing illuminance levels for sun positions that are symmetrical around solar noon showed differences that favour the morning sun positions, as the system was originally designed (see Figure 14-4.1). At an altitude of 34°, if, for example, we compare an azimuth of 30° to the east of south to an altitude of 30° west of south, a ratio of 1.08 is measured between the two averaged levels of illuminance.

Figure 4-14.5 (left) shows an external view of the test module, equipped with the anidolic solar blind on the upper window. A fabric roller blind (made of thick dark brown fabric with a visible transmittance of 4%) was left in place behind the lower part of the window. Figure 4-14.5 (right) is a fish-eye view of the room interior, taken on a clear day, showing the system's redirection of sunlight deep into the room. The luminance mapping in the figure (corresponding to the field of view of a user seated at the rear desk in the room) confirms the glare control achieved by the system.

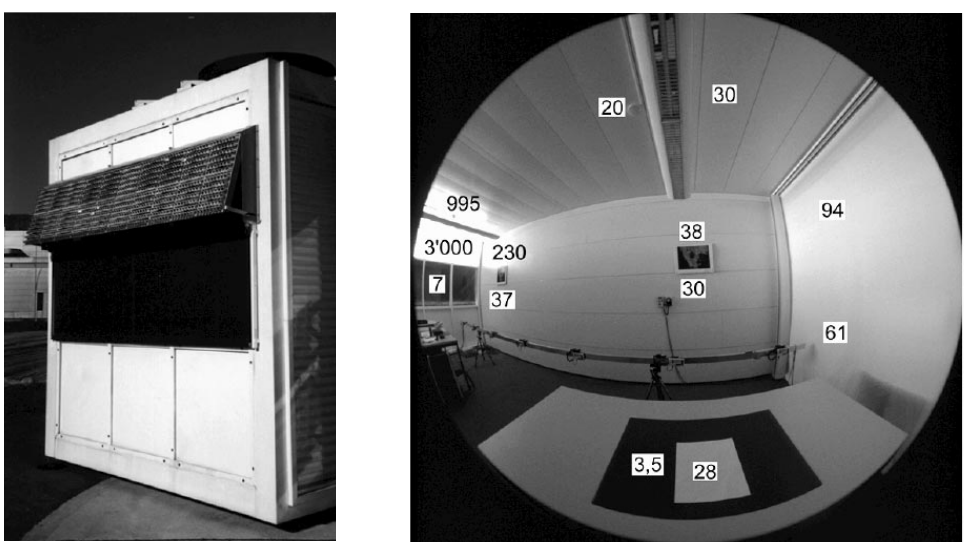


Figure 4-14.5: View of the experimental facade (left); view-field at desk in the rear of the room – luminance in cd/m^2 (right)

Conclusion

The performance of anidolic solar blinds is optimised to introduce sunlight for daylighting without glare. Its redirection and selectivity of sun rays offers significant promise for making sunlighting strategies more effective in mild and sunny climates. These benefits are not offered by other anidolic daylighting systems, which were optimised to work under overcast conditions with diffuse daylight.